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Parametric Approach to Thin-Route Earth-Station Requirements

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NTIA Report 82-99•Parametric Approach to Thin-Route th-Station Requirements

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Parametric Approach to Thin-Route Earth-Station Requirements

R.D. Jennings

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

Bernard J. Wunder, Jr., Assistant Secretary
for Communications and Information

March 1982

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II

PREFACE

The analysis reported here has been done for the Agency for International Development (A.I.D.), U.S. Department of State, by the Institute for Telecommunication Sciences (ITS), a laboratory in Boulder, Colorado, of the National Telecommunciations and Information Administration. The report presents a parametric analysis of earth-station design for thin-route applications suited to the A.I.D. Rural Satellite Program. This A.I.D. Program is a multiyear, cooperative effort, between the United States and a number of developing nations, which seeks to demonstrate appropriate narrowband uses of satellite technology as a development tool in education, agriculture, health, and other sectors within each cooperating nation.

This support to the A.I.D. has been provided under Participating Agency Service Agreement (PASA) CG/DSB-5811-1-79. Administrative and technical monitoring of this support analysis was performed by Mr. Robert Schenkkan and Dr. Lawrence Frymire for the A.I.D. Technical direction and management supervision of the analysis at ITS was provided by Dr. Peter McManamon.

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PARAMETRIC APPROACH TO THIN-ROUTE EARTH-STATION REQUIREMENTS

R. D. Jennings*

Satellite communications are likely to be used to provide thin-route telephone service in developing countries only if the cost of earth stations can be substantially reduced. A parametric analysis of earth-station design and service capabilities is presented. Parameters of the analysis include six values of earth-station figure of merit, G/T, ranging from 17.5 to 30.0 dB/K, five values of antenna diameter ranging from 3.0 to 10.0 m, low-noise amplifier temperatures ranging from 55 to 200K, high-power amplifier output powers ranging from 1 to 400 W, INTELSAT and Palapa (typical of many domestic satellites) satellite resources, and frequency modulation as well as digital encoding with phase shift keying for voice service. Link budgets are developed from which the numbers of carriers that can be supported by 1/4 transponder are calculated. Assuming single channel per carrier as well as multiple channels per carrier service, the numbers of duplex telephone circuits per 1/4 transponder are calculated. Traffic analyses are performed to demonstrate the relationships between numbers of telephone subscribers per earth station, numbers of circuits provided at each earth station, and quality of service. Sampled cost information is presented and used to estimate earth station costs.

Key words: earth-station cost; earth-station design; satellite communications; telephone; thin-route applications; traffic analysis

1. INTRODUCTION

1.1 Background

Satellite technology is well suited for providing communications to users (including public service users) that are remotely located and at locations that are widely separated. These user-location characteristics are common in developing countries as well as rural areas of developed countries. There is at least a two-fold basis to argue for satellite-based communications for such areas. First, using satellite technology, there are no requirements to construct extensive, land-based facilities, such as telephone lines and/or HF radio or microwave relay stations, across the terrain separating these remote locations. Often, the terrain separating these remote locations is very unfriendly, i.e., rugged mountains, dense forests and other vegetation, deserts, vast snow and ice fields, oceans, etc. Secondly, the costs for installing and using satellite-based technology are independent, to a considerable degree, of distances between remote and widely dispersed locations. Assuming leased satellite transponders, or fractions thereof, are used to provide satellite-based communications services, some differences in cost are realized as a consequence of available satellite transponder space for lease and the lease arrangements with regard to service interruptions.

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*The author is with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO 80303.

A significant and important cost consideration to satellite communications being utilized by remotely located and widely separated users is the cost of earth stations for the remote locations. Research and development efforts during the past 15 years on satellite communications technologies have been devoted extensively and primarily to the development of technologies to provide improved service and voice circuit capacities for high volume, geographically centralized users. Substantial success has been realized, too. For example, current technology can provide 12,000 telephone calls plus two color television channels through an INTELSAT V satellite. Commonly, the communications needs for users at remote and widely separated locations will be short-term, intermittent, and low traffic-volume demands. Such requirements have become known as "thin-route" requirements. Prior to the relatively recent market demands by business, industry, government, and institutional organizations for data exchange and transfer through domestic satellites, there has been little economic incentive for development of small-aperture antennas and other earth station hardware to support the requirements of thin-route communications. There are, however, many opportunities waiting and developing in the less developed countries and in rural areas of developed nations, such as in the United States, where the satellite communications technology tailored to thin-route requirements can and needs to be applied.

At present, and for the next several years, the best-suited satellite capabilities available for lease to serve developing countries and other rural locations with basic communication services operate at C-band (5.925 to 6.425 GHz for earth-to-space transmission and 3.700 to 4.200 GHz for space-to-earth transmission). The analysis and discussion of this report apply particularly to these bands of operation.

The Agency for International Development (A.I.D.) has embarked on a multiyear program to help develop satellite communications technologies suited to establishing basic, reliable communications systems in rural and under-developed areas of the world. A second part of the program is to cooperate with selected countries in projects to demonstrate the usefulness of these technologies applied to providing basic health, agricultural, and educational services to rural populations. The program is known as the A.I.D. Rural Satellite Program.

1.2 Analysis Objective

The purpose of this report is to define system requirements and a low-cost, earth-station design which will satisfy those program requirements. The earth-station design must be suited to providing cost-effective, low-volume, satellite communications in rural and widely separated locations. These requirements, service offerings, and designs are discussed in the context of available satellite capabilities to provide the space segment of a communications system. In addition, various service concepts, voice encoding technologies, and other service features of a possible communications system are considered in establishing the system design. A parametric approach is taken in defining service requirements and establishing a system design to satisfy those requirements. This approach has been taken because the anticipated requirements vary substantially from one application to another, and typical requirements are too general to be useful in establishing system design. This parametric, or matrix, approach provides convenience in applying the design information to a broad range of application situations.

1.3 Service Requirements (Typical Thin-Route Applications)

Thin-route services that typically will be established under various projects of the Rural Satellite Program (or other, introductory rural communications plans) are assumed to be an initiation of basic telephony where there has been none or a substantial improvement of basic telephony where a poorly functioning capability has existed. Further, it is assumed that an emphasis in establishing telephony service will be to provide two-way, participatory communications which will facilitate training and consultation services to rural users. Two-way, participatory communications are essential for health and agricultural consultation as well as for training and general educational development services to rural populations in less developed countries.

Telephone service may be supplemented initially by modest capabilities for teletype (TTY) to accommodate data transfer. Other voice-band capabilities such as facsimile or slow-scan television may be added as demands develop; however, such capabilities are not expected as part of the initial service complement.

In some applications, a radio broadcast service may be desired to provide information, non-participatory training, and entertainment to the rural populace.

No consideration is given in this report to television service because the satellite transponder bandwidth to support television service is substantial and expensive. Nominally, a television channel would require a full transponder using present technology. Programming production also would be expensive.

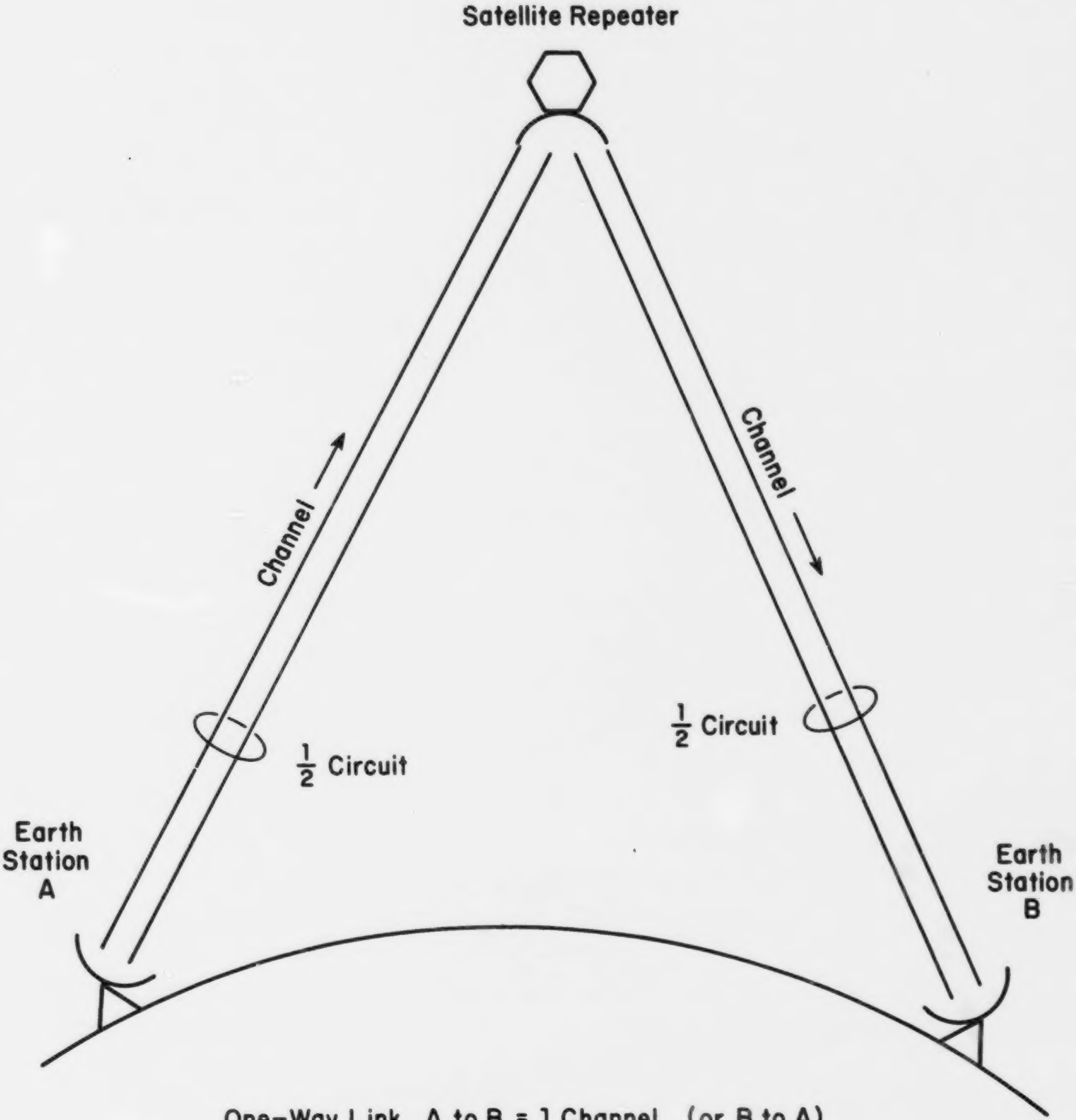
1.4 Networking Considerations

A circuit is defined as a full, two-way link (duplex telephone service) between two earth stations. Figure 1 provides graphical illustration of the circuit definition. The available power is designated as the satellite's effective isotropically radiated power (EIRP). The circuits that can be supported then may be apportioned as desired to the earth stations comprising a network. We assume that communications may be established in either a STAR or MESH network of earth stations with as few as two earth stations. These network configurations are illustrated graphically in Figure 2.

STAR networks are considered as one or more remote earth stations (which have limited capability and capacity) each linked only with a central or master earth station. In this analysis we assume the central earth station of a STAR network is an INTELSAT Standard B or equivalent capability station, and the remote stations are identical in design capability. MESH networks are considered to be formed by two or more earth stations each capable of linking directly with every other station in the network. We assume the earth stations in a MESH network have identical receiving system figures of merit (gain-to-noise temperature ratios, G/T) and high power-amplifier capacities for this design analysis. (Of course, the assumption of identical earth stations within a network is reasonable only if the same numbers of circuits and types of service are utilized for each location.)

The analysis does not explicitly consider a maximum number of earth stations for a network. Rather, the analysis determines maximum numbers of circuits that can be supported by the power available for transmission from the satellite providing the space segment.

Connectivity is a term used in this report to describe the communication linking between earth stations. This linking is illustrated in Figure 2 by arrows. Full connectivity may be achieved in a MESH network. That is, each station of the network can establish a circuit with any other station of the network. The total number of circuits that may be established simultaneously is controlled by the available satellite EIRP and the circuit equipment capabilities

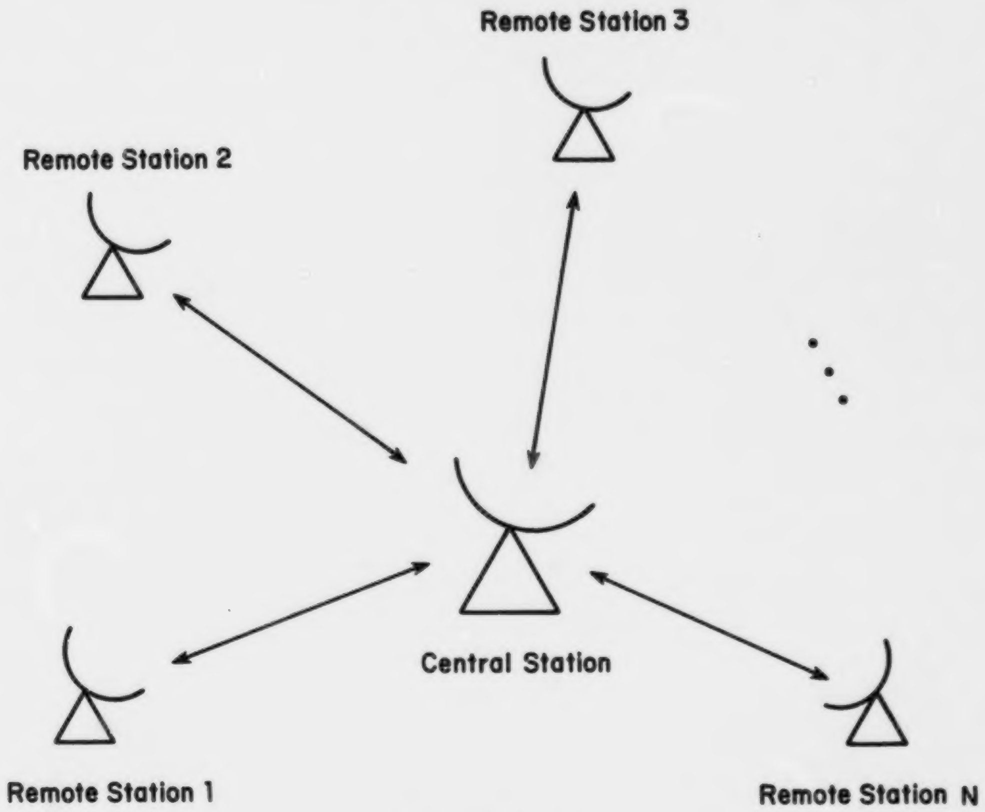

Satellite Repeater
Channel
Channel
$\frac{1}{2}$ Circuit
$\frac{1}{2}$ Circuit
Earth Station A
Earth Station B

One-Way Link, A to B = 1 Channel (or B to A)

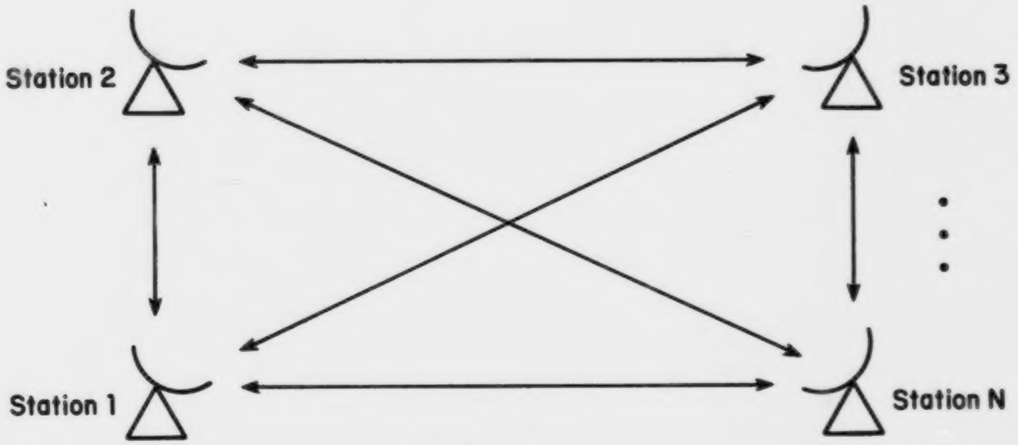
Two-Way Link, A to B = 1 Circuit (Duplex Operation)

(Two-Way Link, Earth Station to Satellite = $\frac{1}{2}$ Circuit)

Figure 1. Graphic illustration of channel and circuit terminology for satellite communications.


Remote Station 3
Remote Station 2
Central Station
Remote Station 1
Remote Station N

STAR Network


Station 2
Station 3
Station 1
Station N

MESH Network

Figure 2. Network configurations graphically illustrated.

of the earth stations comprising the network. STAR networks offer restricted connectivity. In such a network, circuits can be established only between the central earth station and each of the remote earth stations. Communications between two remote earth stations can be achieved only by establishing circuits between the central earth station and each of the two remote earth stations with a patch connection at the central station. Of course, this type of communications connection between the two remote earth stations has the undesirable feature of delay equivalent to the propagation time for two round trips of the signal between earth and the satellite repeater, twice the delay in a MESH network connection.

Earlier we mentioned that an important service requirement for the Rural Satellite Program (sponsored by A.I.D.) would be two-way, participatory communications for which we shall use the term teleconferencing. Such service will be important for providing training and other social services to the users of a rural satellite system. In Figure 1 the linking arrows represent circuits when considering station-to-station, duplex telephony service between two users. For teleconferencing, however, use of (full) duplex service would create increasing confusion as the number of participants increase, unless very strict protocol were practiced. Considerable reduction to protocol requirements for teleconferencing is realized by using push-to-talk telephone sets. Service with push-to-talk telephone sets typically is known as half-duplex service.

The ultimate teleconferencing capability would be realized if linking could be established simultaneously between all earth stations in the network. Now, however, the linking arrows represent channels (refer to Figure 1) because of the half-duplex service. That is, each station could transmit a signal that would be received by all of the remaining stations, and each station would have receiving equipment to allow simultaneous reception of transmissions from all other stations in the network.

Another approach to teleconferencing in thin-route service applications follows the STAR network concept. One earth station functions as a central station providing "broadcast" transmission (through the satellite repeater) to each (other) station in the network, and each remote station establishes a communication channel with the central station. The principal disadvantage for this scheme is that communications originating from a remote station cannot be received by other remote stations. A solution to this problem may be possible, however, by re-transmission from the central station of communications originating from a remote station. Operational protocol must be established to cope with the delay resulting from propagation time for the second earth-satellite-earth transmission of the signal.

A teleconferencing capability requires equipment at each earth station that would not be required for basic telephony between two users (or locations). Additional equipment means additional cost for the earth station above that cost for simply providing location-to-location, duplex telephony. In a STAR teleconferencing network the additional cost would be independent of the number of stations in the network. However, the increased cost would be proportional to the number of participating stations in a MESH network.

1.5 Remote Earth-Station Configuration

The principle components of an earth station for satellite, telephone communications are identified in the block diagram in Figure 3. Considerable emphasis is given to the use of "small" earth terminal antennas to provide economical communications in thin-route applications. Defining the size of a small-aperture antenna is, indeed, rather a matter of judgment, but is entirely dependent upon the service to be provided and the satellite to be used in providing the service. Following the parametric or matrix approach mentioned earlier, this analysis considers antenna apertures which range from 3 m to 10 m in diameter for the remote station. An earlier report (Wells, 1978) discusses small earth terminal developments to that time. With reference to that report, this report discusses current developments and status for small earth-terminal technology.

In addition to the antenna, other earth-station components and characteristics that are considered in this analysis include the antenna feed; the low-noise amplifier (LNA), type and noise temperature; receiving-system figure of merit, defined as the ratio of antenna gain to system noise temperature (G/T) expressed in decibels; the high-power amplifier (HPA), type and operating output power; voice modulation and encoding techniques; and radio frequency (rf) modulation techniques. Voice and rf modulation/encoding techniques considered include single channel per carrier frequency modulation (SCPC-FM), digital voice encoding such as adaptive delta modulation (ADM) with phase shift keying (PSK) for rf modulation, either SCPC or multiple channels per carrier, and digital voice synthesis such as linear predictive coding (LPC) or adaptive predictive coding (APC) with PSK for rf modulation, SCPC or multiple channels per carrier. Analytical emphasis is on the tradeoffs that are possible in antenna size, LNA characteristics, HPA character-

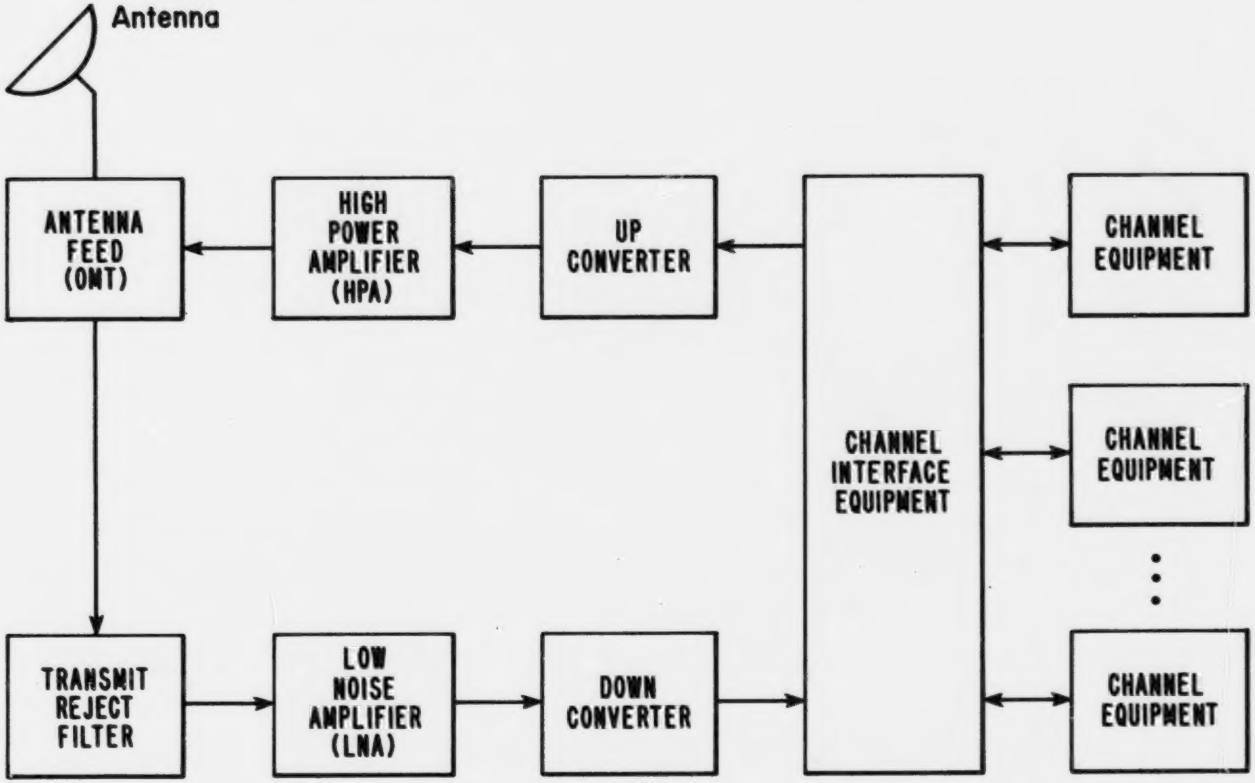

Antenna
ANTENNA FEED (OMT)
HIGH POWER AMPLIFIER (HPA)
UP CONVERTER
CHANNEL INTERFACE EQUIPMENT
CHANNEL EQUIPMENT
CHANNEL EQUIPMENT
CHANNEL EQUIPMENT
TRANSMIT REJECT FILTER
LOW NOISE AMPLIFIER (LNA)
DOWN CONVERTER

Figure 3. Block diagram of an earth station for telephone communications via satellite.

istics, and satellite transponder characteristics to provide basic telephone service using the techniques identified above.

1.6 Available Resources for Satellite-Transponder Bandwidth

The International Telecommunications Satellite Organization (INTELSAT) practices leasing "spare" communication capacity on its operational satellites to member nations for the development of domestic communications (Kelley, 1978). There are at least 16 nations with domestic communications using INTELSAT leased transponder capacity (Kelley, 1980). INTELSAT resources are among the most likely space segment resources to be used for RSP applications, at least during initial, experimental projects. Resources for lease are available on operational INTELSAT IV, IV-A, and V satellites. For INTELSAT IV and IV-A, the lease service definitions are summarized in a report by Kelley (1978). Leased service definitions for INTELSAT V also have been established recently (INTELSAT, 1981). The minimum capacity that can be leased is 1/4 transponder.

Rural satellite program applications in the area of Indonesia and the Philippines may be introduced or existing services expanded using Palapa System satellites. The two Palapa A satellites have been in service for several years. New, Palapa B satellites are scheduled for launch in 1983 and 1984. The Palapa System satellites' technical characteristics are typical for many domestic satellite systems such as ANIK, WESTAR, SATCOM, and COMSTAR.

2. DESIGN ANALYSIS

2.1 Parameter Values

Analyses to establish earth station designs have followed a straightforward approach for determining the carrier-to-noise power density required for several types of voice service. Then the required carrier-to-noise power density values are used in link budget calculations to determine the required satellite power per carrier. Following the parametric concepts for these analyses, four selected values of carrier-to-noise power density, three types of leased satellite transponder resources and seven values for earth station receiving figure of merit (G/T) are used in the link budget calculations. These values and transponder resource assumptions are shown in Table 1.

Table 1. Parameter Values Used in Link Budget Calculations to Determine Satellite Transponder Power (EIRP) Required as a Function of Carrier-to-Noise Power Density, Earth Station Design, and Station Networking

Parameter (Units)	Parameter Values
Carrier-to-Noise Power Density, C/N_0 (dB-Hz)	48.0, 51.0, 54.0, and 57.0
Antenna Gain-to-System Noise Temperature, G/T (dB/K)	17.5, 20.0, 22.5, 25.0, 30.0, and 31.7*
Antenna Diameter (m)	3.0, 4.5, 6.0, 8.0, 10.0, and 11.0*
Low Noise Amplifier (LNA) Temperature Range (K)	55 to 200
High Power Amplifier (HPA) Output Power Range (W)	1 to 400
Satellite Resource, 1/4 Transponder (9 MHz)	INTELSAT, Global Beam Coverage INTELSAT, Hemispheric Beam Coverage Palapa A
Station Networking	MESH and STAR with INTELSAT Standard B or equivalent central station

*Considered only as the central station in a STAR network.

Various types of voice service technology are possible within the range of carrier-to-noise power density values that are considered. These technologies include single channel per carrier (SCPC) frequency modulation (FM), digitally encoded voice using adpative delta modulation (ADM), and digitally synthesized voice such as linear predictive coding (LPC). Digital techniques are assumed to be implemented with phase shift keying (PSK), either two phase (binary) or four phase (quadrature). Additionally, digital technology may utilize forward error correction (FEC) coding to reduce bit errors. Finally, digital technology may be used to provide single channel per carrier service or multiplexing may be performed to achieve two channels per carrier (2CPC), three channels per carrier (3CPC), or four channels per carrier (4CPC). The required carrier-to-noise power density values for various combinations of technologies are shown in Table 2. Technical details and calculation methodology for the values in Table 2 are contained in Appendix A.

The three types of satellite leased transponder resources considered in the design analysis are INTELSAT with global beam coverage, available on INTELSAT IV, IV-A, and V; INTELSAT with hemispheric beam coverage, available on INTELSAT IV-A and V; and Palapa. The downlink EIRP available from 1/4 transponder for each type

Table 2. Required Carrier-to-Noise Power Density, C/N_0, Values for Various Choices of Voice Encoding, Forward Error Correction (FEC) Coding, and Modulation Techniques; BER = 10^{-4}

Voice Encoding and RF Modulation Technique	Required C/N_0 (dB-Hz)			20 dB Bandwidth (KHz) (99% Avg. Spectral Energy)			Minimum Channel Spacing (KHz) 1.5 (Bit Rate)			Ref.
SCPC Companded FM, Phase-locked Loop Detection	53.0			--			--			1
SCPC Companded FM, FM Discriminator Detection	53.8			--			--			1
SCPC DCDM* at 32.0 kbps (with QPSK)	53.7 - 54.5			89.6			24.0			1
	No FEC	R=3/4 FEC	R=1/2 FEC	No FEC	R=3/4 FEC	R=1/2 FEC	No FEC	R=3/4 FEC	R=1/2 FEC	
	(BPSK and QPSK)			(QPSK only)			(QPSK only)			
SCPC ADM at 9.6 kbps	52.2	48.0	46.3	26.9	35.8	53.8	7.2	9.6	14.4	2-6
16.0 kbps	54.4	50.2	48.5	44.8	59.7	89.6	12.0	16.0	24.0	2-6
32.0 kbps	57.4	53.2	51.5	89.6	119.5	179.2	24.0	32.0	48.0	2-6
2CPC ADM at 9.6 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	2-6
16.0 kbps	57.4	53.2	51.5	89.6	119.5	179.2	24.0	32.0	48.0	2-6
32.0 kbps	60.5	56.3	54.6	179.2	238.9	358.4	48.0	64.0	96.0	2-6
3CPC ADM at 9.6 kbps	57.0	52.8	51.1	80.6	107.5	161.3	21.6	28.8	43.2	2-6
16.0 kbps	59.2	55.0	53.3	134.4	179.2	268.8	36.0	48.0	72.0	2-6
32.0 kbps	62.2	58.0	56.3	268.8	358.4	537.6	72.0	96.0	144.0	2-6
4CPC ADM at 9.6 kbps	58.2	54.0	52.3	107.5	143.4	215.0	28.8	38.4	57.6	2-6
16.0 kbps	60.5	56.3	54.6	179.2	238.9	358.4	48.0	64.0	96.0	2-6
32.0 kbps	63.5	59.3	57.6	358.4	472.9	716.8	96.0	128.0	192.0	2-6
2CPC LPC at 4.8 kbps	52.2	48.0	46.3	26.9	35.8	53.8	7.2	9.6	14.4	2-6
9.6 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	2-6
4CPC LPC at 4.8 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	2-6
9.6 kbps	58.2	54.0	52.3	107.5	143.4	215.0	28.8	38.4	57.6	2-6

*DCDM denotes Digitally Controlled-Slope Delta Modulation.

Reference 1: Campanella, et al. (1977).
Reference 2: Gray (1981).
Reference 3: Jacobs (1974).
Reference 4: Nesenbergs (1975).
Reference 5: Oetting (1979).
Reference 6: Spilker (1977).

satellite is shown in Table 3. Additional transponder technical characteristics for these satellite resources are listed in Appendix B.

Table 3. Downlink EIRP For Leased Satellite Services Using 1/4 Transponder

Satellite Resource	1/4 Transponder Operating EIRP	
	dBW	Watts
INTELSAT Global Beam*	11.5	14.1
INTELSAT Hemispheric Beam**	14.0	25.1
Palapa A	22.0	158.5
Palapa B	24.0	251.2

*Available on INTELSAT IV, IV-A, and V Satellites
**Available on INTELSAT IV-A and V Satellites

2.2 Parameter Dependencies

Earth station components and characteristics important to the design analysis are shown in Table 1. A link budget calculation requires (or determines) explicit values for antenna gain-to-system noise temperature ratio (G/T) for the receiving earth station and antenna gain and high-power amplifier (HPA) output power for the transmitting earth station. And, of course, these values are dependent. For example, a designer selects the receiving earth station's figure of merit (G/T), and the link budget calculation shows the required uplink power from the transmitting earth station. Required uplink power is achieved by proper combination of antenna size (which determines gain) and high-power amplifier output power.

The receiving system antenna gain (calculated from size) and low-noise amplifier operating temperature are related to figure of merit (G/T) as shown by Figure 4. For example, G/T = 22.5 dB/K may be realized using a 4.5-m antenna and a low-noise amplifier with noise temperature of ∿90K or using a 6.0-m antenna and a low-noise amplifier with noise temperature of ∿190K. Calculation of antenna gain, which is a function of antenna size and the frequency of the electromagnetic energy is discussed in Appendix C.

The transmitting antenna gain (calculated from size) and output power of the high-power amplifier are related to the effective isotropically radiated power (EIRP) for the uplink as shown in Figure 5. For example, if the required uplink EIRP is 60.0 dBW and the station will use a 6.0-m antenna (determined by other factors such as receiving system figure of merit, ease of installation, transportability, cost, etc.), then the HPA output power capability must be at least 12 W.

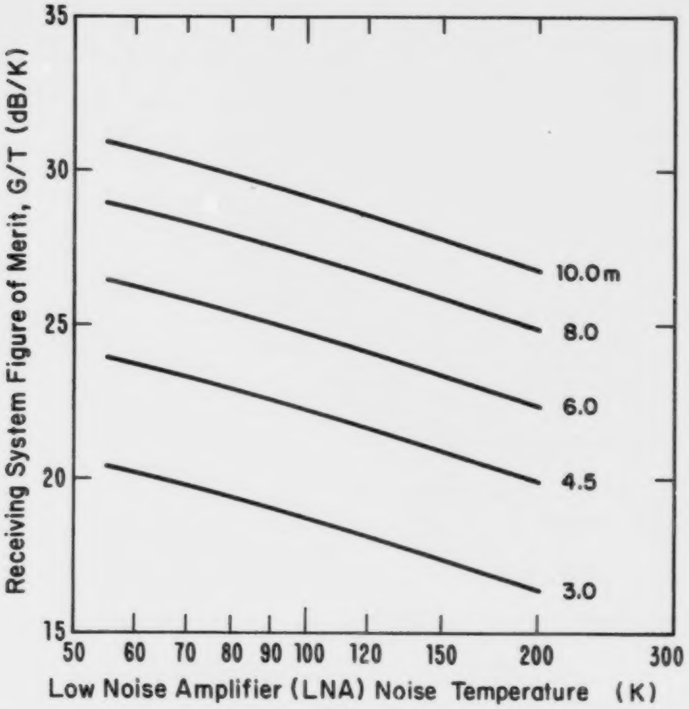


Figure 4. Earth-Station receiving system figure of merit, G/T, as a function of low-noise amplifier noise temperature parametric in antenna diameter (expressed in meters).

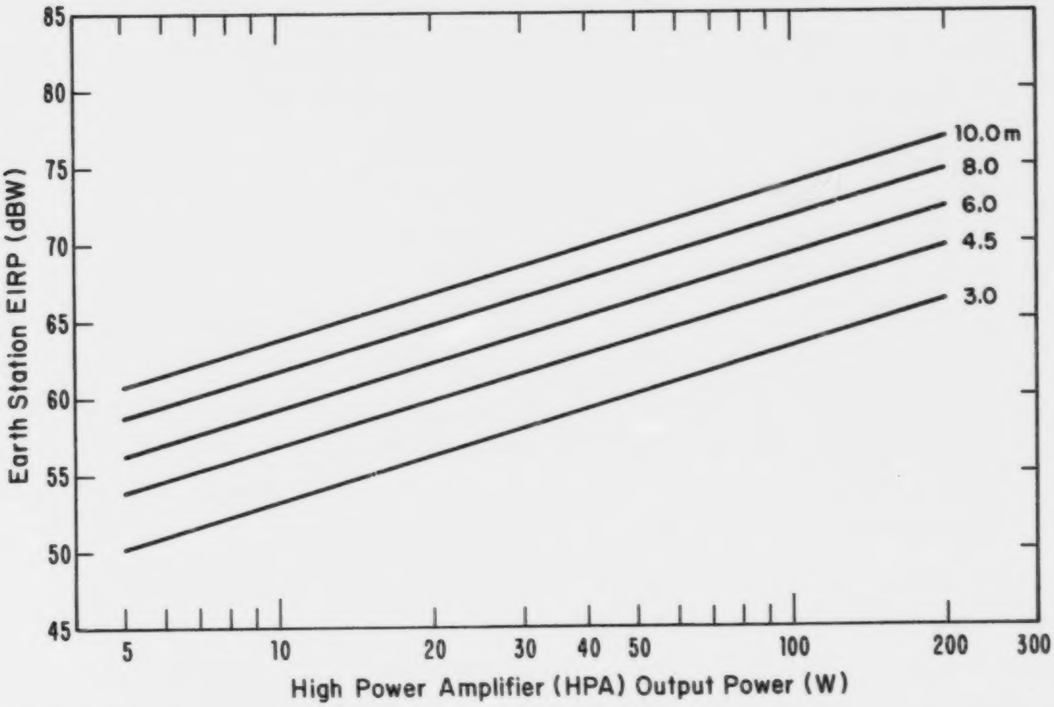


Figure 5. Earth-station EIRP as a function of high power amplifier output power parametric in antenna diameter (expressed in meters).

2.3 Link Budget Calculations

Link budget calculations are performed using the parameter values and satellite resources and networking options shown in Table 1. In total, these calculations have been done for many parameter combinations, which are included in Appendix D. The calculations for one combination of parameters are presented and discussed in this section. The selected values are C/N_0 = 54.0 dB-Hz and INTELSAT global beam coverage for the satellite resource using both MESH and STAR networking.

The worksheets for the link budget calculations include all values of G/T. Table 4 shows the completed worksheet for MESH networking. Calculations for STAR networking require two worksheets, since the central earth station is assumed to be an INTELSAT Standard B or equivalent capability, whereas the remote earth station will be smaller with less capability and capacity. Table 5 shows the worksheet for central-station-to-remote-station link budgets. The remote-station-to-central-station budget worksheet is shown in Table 6.

These link budgets provide two important items of information for the design analysis, given a selection for figure of merit (G/T) for the receiving earth station. First, the satellite EIRP required to support a radio frequency (rf) carrier is shown. In thin-route applications, the available downlink EIRP usually limits the communication capacity of the system. Available bandwidth limitation usually only occurs in large trunking applications. Secondly, the required capacity of the high-power amplifier per rf carrier for the transmitting earth station is shown. This appears as the "XMTR Pwr. to Ant." entry in the worksheet.

2.4 Telephone Channels Supported by Available EIRP

The calculated, required, transponder EIRP per carrier values have been used to produce plots of numbers of telephone channels as a function of the available satellite power. Such plots are shown in Figures 6 and 7 assuming single channel per carrier (SCPC) and two channels per carrier (2CPC) applications. To illustrate the utility of these plots, assume an application will use remote earth stations with G/T = 25.0 dB/K to provide SCPC telephone service. Figure 6 shows that for INTELSAT global beam coverage, 1/4 transponder will support 26 channels maximum with C/N_0 = 54.0 dB-Hz when G/T = 25.0 dB/K for the receiving earth station. Two channels are required to provide one circuit (duplex telephone service); therefore, 13 circuits can be supported by 1/4 transponder in a MESH network, or about 7.7% of the available power is used per circuit.

Table 4. Link Budget for Required C/N_o = 54.0 dB-Hz for a MESH Network using an INTELSAT Global Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budgets

Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
XMTR Pwr. to Ant.*	dBW	29.4	27.3	23.4	21.0	18.5	16.0	13.5	11.1	6.8
	W	871.0	537.0	218.8	125.9	70.8	39.8	22.4	12.9	4.8
XMTR Ant. Gain* (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
Uplink EIRP*	dBW	72.6	70.1		67.7		65.2		62.8	60.4
Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
Uplink Prop. Loss ($\alpha=20°$)	dB	200.2	200.2		200.2		200.2		200.2	200.2
Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3		-95.7		-98.2		-100.6	-103.0
Multi-Carrier Op. Flux Den.	dBW/m^2	-84.0	-84.0		-84.0		-84.0		-84.0	-84.0
Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
Satellite G/T	dB/K	-18.6	-18.6		-18.6		-18.6		-18.6	-18.6
Uplink Rec'd. C/N_o	dB-Hz	81.9	79.4		77.0		74.5		72.1	69.7
Sat. Sys. Gain	dB	132.8	132.8		132.8		132.8		132.8	132.8
Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2		-0.2		-2.7		-5.1	-7.5
	W	3.0	1.7		1.0		0.5		0.3	0.2
Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
Downlink Prop. Loss, $\alpha=20°$	dB	196.3	196.3		196.3		196.3		196.3	196.3
RCV Ant. Gain	dB	----------------------------See Figure 4----------------------------								
RCV Sys. Noise Temp.	dB/K	----------------------------See Figure 4----------------------------								
Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
Downlink Rec'd C/N_o	dB-Hz	54.0	54.0		54.1		54.1		54.2	54.3
Downlink Rec'd C/I	dB-Hz	80.2	77.7		75.3		72.8		70.4	68.0
System C/N_o (Total)	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0
Required C/N_o	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0

*See Figure 5.

Table 5. Link Budget for Required C/N_o = 54.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budgets

Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
XMTR Pwr. to Ant.*	dBW	18.1	15.6	13.2	10.7	8.3	5.9
	W	64.6	36.3	20.9	11.7	6.8	3.9
XMTR Ant. Gain* (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
Uplink EIRP* (6 GHz)	dBW	72.6	70.1	67.7	65.2	62.8	60.4
Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3	-95.7	-98.2	-100.6	-103.0
Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0	-84.0	-84.0	-84.0	-84.0
Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
Satellite G/T	dB/K	-18.6	-18.6	-18.6	-18.6	-18.6	-18.6
Uplink Rec'd. C/N_o	dB-Hz	81.9	79.4	77.0	74.5	72.1	69.7
Sat. Sys. Gain	dB	132.8	132.8	132.8	132.8	132.8	132.8
Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2	-0.2	-2.7	-5.1	-7.5
Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
Downlink Prop. Loss, α=20°	dB	196.3	196.3	196.3	196.3	196.3	196.3
RCV Ant. Gain	dB	-------------------------------- See Figure 4 --------------------------------					
RCV Sys. Noise Temp.	dB/K	-------------------------------- See Figure 4 --------------------------------					
Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
Downlink Rec'd C/N_o	dB-Hz	54.0	54.0	54.1	54.1	54.2	54.3
Downlink Rec'd C/I	dB-Hz	80.2	77.7	75.3	72.8	70.4	68.0
System C/N_o (Total)	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0
Required C/N_o	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0

*See Figure 5.

Table 6. Link Budget for Required C/N_o = 54.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
XMTR Ant. Gain* (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
XMTR Pwr. to Ant.*	dBW	15.6	12.1	9.6	7.1	5.2
	W	36.3	16.2	9.1	5.1	3.3
Uplink EIRP*	dBW	58.8				
Misc. Uplink Losses	dB	0.5				
Uplink Prop. Loss (α=20°)	dB	200.2				
Pwr. Flux Den. at Sat.	dBW/m^2	-104.6				
Multi-Carrier Oper. Flux Density	dBW/m^2	-84.0				
Boltzmann's Constant	dBW/K-Hz	-228.6				
Satellite G/T	dB/K	-18.6				
Uplink Rec'd. C/N_o	dB-Hz	68.1				
Sat. System Gain	dB	132.8				
Sat. EIRP per Carrier (4 GHz)	dBW	-9.1				
	W	0.1				
Sat. Int. Pwr.	dB-Hz	-76.0				
Misc. Downlink Losses	dB	0.5				
Downlink Prop. Loss, α=20°	dB	196.3				
RCV Ant. Gain	dB	STD "B"				
RCV Sys. Noise Temp.	dB/K	STD "B"				
Earth Station G/T (Std. "B")	dB/K	31.7				
Downlink Rec'd C/N_o	dB-Hz	54.4				
Downlink Rec'd C/I	dB-Hz	66.4				
System C/N_o (Total)	dB-Hz	54.0				
Required C/N_o	dB-Hz	54.0				

*See Figure 5.

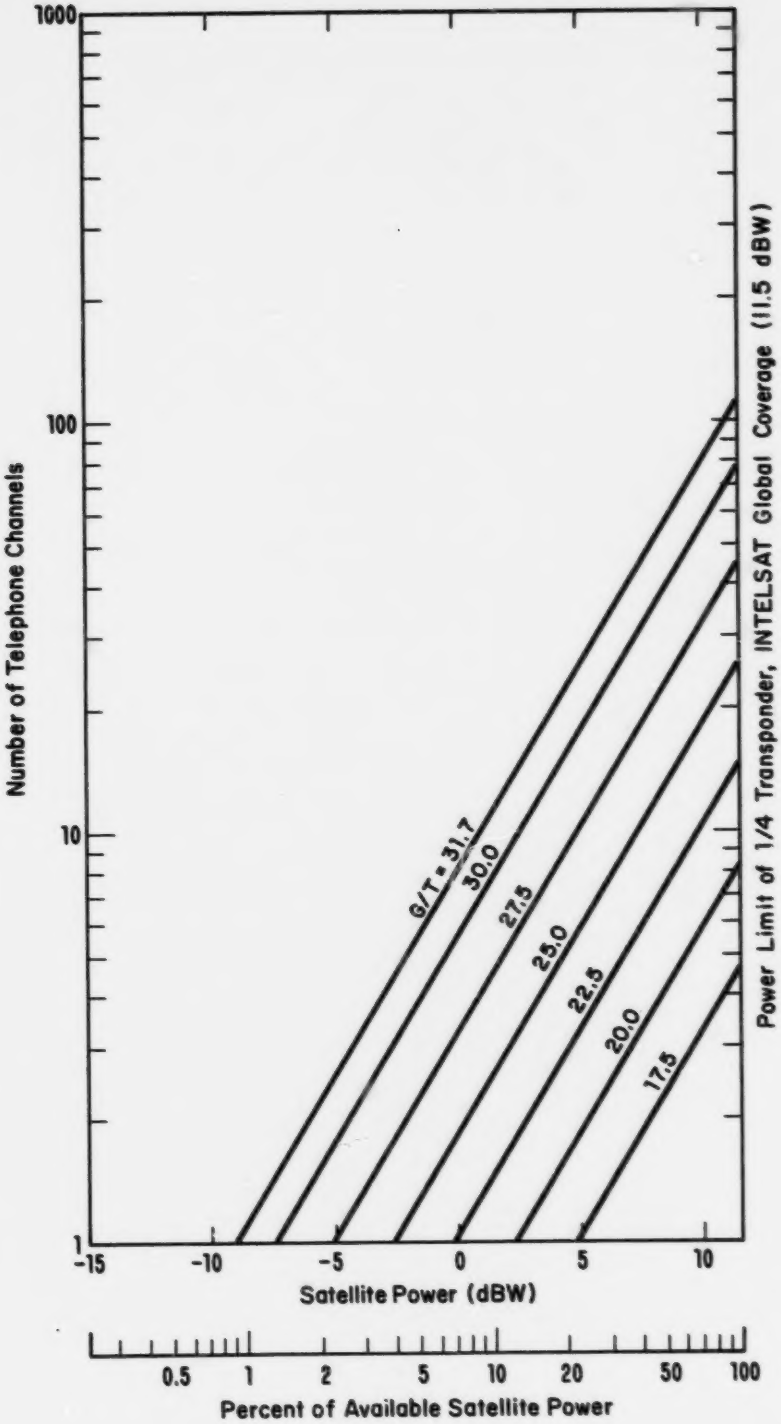


Figure 6. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0=54.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW(14.1W), 1/4 transponder for INTELSAT global beam coverage. See Figure 4 for relationship between G/T, antenna size, and LNA noise temperature.

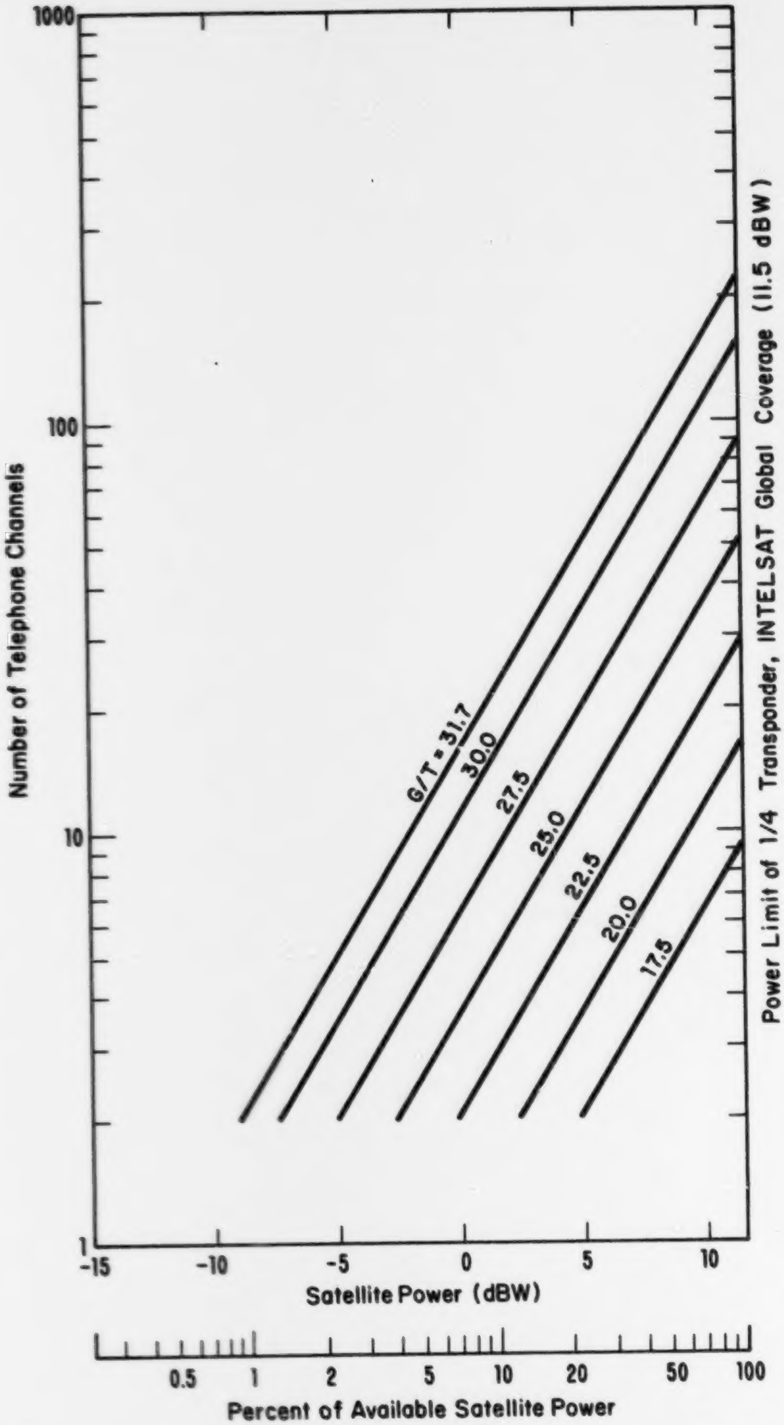


Figure 7. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using two channels per carrier) providing C/N_0=54.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW(14.1W), 1/4 transponder for INTELSAT global beam coverage. See Figure 4 for relationship between G/T, antenna size, and LNA noise temperature.

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If the application is in a STAR network, where an INTELSAT Standard B or equivalent central earth station is assumed, only half of the channels used for the duplex circuits are received by the "small," remote earth stations. The other half of the channels are received by the central earth station. Referring again to Figure 6, we see that one channel received by the central earth station (G/T = 31.7 dB/K) requires less than 1% of the available transponder EIRP, and one channel received by the remote earth station (G/T = 25.0 dB/K) requires a little less than 4% of the available transponder EIRP. Therefore, one circuit in the STAR network requires only about 4.7% of the available transponder power. A total of 21 circuits can be supported simultaneously by the EIRP for the 1/4 transponder.

Tables 7 and 8 show the total numbers of circuits, in MESH and STAR networks, respectively, which can be supported by 1/4 transponder for each of the assumed satellite resources and for each of the parameter values considered for required carrier-to-noise power density and earth station antenna gain-to-receiving system noise temperature. The two values derived in the preceding paragraphs are shown in the appropriate row and column of each table. In the following section, these data are used to develop design results which relate to "customer requirements" rather than "engineering requirements" such as used in the design analysis.

When the system application uses a digital voice technology, it is possible and may be desirable to offer two (or more) channels per carrier by multiplexing the digital data for each channel into a single bit stream. For two channels per carrier, it is obvious that the numbers of circuits that can be offered with either networking scheme are double the numbers possible using SCPC. The curves in Figure 7 also may be used, following the method just described, to verify these conclusions.

3. DESIGN RESULTS

In the preceding section, we have discussed the concept that available transponder power (EIRP) determines the number of telephone circuits that can be provided for given conditions of required carrier-to-noise power density, antenna-gain-to-receiving-system noise temperature, and earth station networking. Numbers of circuits for all combinations of these technical parameters are given in Tables 7 and 8. The methodology of following a parametric approach in the design analysis will continue to be applied in the selections of reasonable ranges (or bounds) for expected requirements. This methodology will be used to develop two types of analysis results.

Table 7. Total Numbers of Telephone Circuits in a MESH Network That Can Be Supported By 1/4 Transponder For C/N_0 = 48.0, 51.0, 54.0, and 57.0 dB-Hz and Receiving Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K

Transponder Resource	C/N_0 (dB-Hz)			
	48.0	51.0	54.0	57.0
G/T = 17.5 dB/K				
INTELSAT, Global Beam*	9	4	2	1
INTELSAT, Hemi Beam**	16	8	4	2
Palapa A	104	52	26	13
G/T = 20.0 dB/K				
INTELSAT, Global Beam*	16	8	4	2
INTELSAT, Hemi Beam**	29	14	7	3
Palapa A	184	92	46	23
G/T = 22.5 dB/K				
INTELSAT, Global Beam*	29	14	7	3
INTELSAT, Hemi Beam**	52	26	13	6
Palapa A	322	161	80	40
G/T = 25.0 dB/K				
INTELSAT, Global Beam*	51	25	13	6
INTELSAT, Hemi Beam**	92	46	23	11
Palapa A	555	278	139	69
G/T = 27.5 dB/K				
INTELSAT, Global Beam*	90	45	22	11
INTELSAT, Hemi Beam**	162	81	40	20
Palapa A	941	472	236	118
G/T = 30.0 dB/K				
INTELSAT, Global Beam*	156	78	39	19
INTELSAT, Hemi Beam**	282	141	70	35
Palapa A	1545	774	388	194

*Available on INTELSAT IV, IV-A, and V Satellites

**Available on INTELSAT IV-A and V Satellites

Table 8. Total Numbers of Telephone Circuits in a STAR Network (Central Station is Assumed to be an INTELSAT Standard B or Equivalent) That Can Be Supported by 1/4 Transponder For C/N_0=48.0, 51.0, 54.0, and 57.0 dB-Hz and Remote Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K

Transponder Resource	C/N_0 (dB-Hz)			
	48.0	51.0	54.0	57.0
G/T = 17.5 dB/K				
INTESLAT, Global Beam*	18	9	4	2
INTELSAT, Hemi Beam**	32	16	8	4
Palapa A	199	99	50	25
G/T = 20.0 dB/K				
INTELSAT, Global Beam*	30	15	7	3
INTELSAT, Hemi Beam**	55	27	13	6
Palapa A	338	169	85	42
G/T = 22.5 dB/K				
INTELSAT, Global Beam*	52	26	13	6
INTELSAT, Hemi Beam**	93	46	23	11
Palapa A	558	279	140	70
G/T = 25.0 dB/K				
INTELSAT, Global Beam*	84	42	21	10
INTELSAT, Hemi Beam**	151	75	37	19
Palapa A	879	440	220	110
G/T = 27.5 dB/K				
INTELSAT, Global Beam*	129	64	32	16
INTELSAT, Hemi Beam**	232	116	58	29
Palapa A	1301	652	326	163
G/T = 30.0 dB/K				
INTELSAT, Global Beam*	184	92	46	23
INTELSAT, Hemi Beam**	333	167	83	42
Palapa A	1781	892	447	224

*Available on INTELSAT IV, IV-A, and V Satellites
**Available on INTELSAT IV-A and V Satellites

3.1 Circuit Analysis Results

The first type of analysis results given is a series of tables showing the percentages of available (1/4 transponder) EIRP required to provide 10, 20, 50, and 100 circuits in MESH and STAR networks. The parametric values defined earlier for carrier-to-noise power density and earth-station antenna gain to receiving-system noise temperature (G/T) have been used in the analysis for each type of satellite resource. The results are given in Tables 9, 10, and 11. To illustrate the utility of these results, refer to Table 9. We see that if C/N_0 = 57.0 dB-Hz were required, 1/4 transponder on an INTELSAT global beam coverage satellite could not provide even ten circuits for a MESH network, unless the receiving earth station figure of merit (G/T) were 27.5 dB/K or greater. Of course, C/N_0 = 57.0 dB-Hz probably is unrealistically high for thin-route applications. However, C/N_0 = 54.0 dB-Hz is reasonable for SCPC-FM applications, and we can interpolate to conclude that only about 13 circuits could be provided using earth stations with G/T = 25.0 dB/K. (Of course, this conclusion agrees with the results shown in Table 8.) Referring to Figure 4, we see that the earth-station antenna diameter would be at least 6.0 m.

At the other extreme for carrier-to-noise power density, if acceptable service can be realized with C/N_0 = 48.0 dB-Hz, we see that about 16 circuits could be provided in a MESH network of earth stations with G/T = 20.0 dB/K (verfied by reference to Table 7). This figure of merit can be achieved using a 3.0-m antenna.

3.2 Traffic Analysis Results

The results discussed in Section 3.1 do not address the questions of numbers of earth stations in a network, the traffic load offered to each earth station and the network, and the numbers of circuits required in the network to support the offered traffic. Traffic load is dependent upon the numbers of telephones serviced by each earth station, the frequency of calls, the length of calls, and acceptable probability for completing a call without encountering busy circuit conditions (often referred to as blocking probability). These several considerations are addressed by traffic analysis for assumed conditions. Traffic analysis, then, provides the second type of results. We believe these results are of considerable utility in determining a system design which satisfies the customer's requirements. One reason for this utility is that the design results are expressed in terms matching the terms used to define the (assumed) customer's requirements.

Table 9. Percentages of Available EIRP from 1/4 Transponder, INTELSAT Global Beam Coverage Satellite, Required to Provide Indicated Numbers of Circuits (Duplex Telephone) for C/N_0=48.0, 51.0, 54.0, and 57.0 dB-Hz and Remote Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K in a Single Channel per Carrier (SCPC) Application

	STAR Network				MESH Network			
No. of Circuits	10	20	50	100	10	20	50	100
Remote Earth Station G/T (dB/K)				C/N_0 = 48.0 dB-Hz				
17.5	55.6	>100	>100	>100	>100	>100	>100	>100
20.0	32.3	64.4	>100	>100	60.1	>100	>100	>100
22.5	19.1	38.3	95.7	>100	33.8	67.6	>100	>100
25.0	11.9	23.8	59.4	>100	19.3	38.6	96.6	>100
27.5	7.8	15.5	38.7	77.5	11.0	22.1	55.2	>100
30.0	5.4	10.9	27.1	54.3	6.4	12.8	32.0	64.0
				C/N_0 = 51.0 dB-Hz				
17.5	>100	>100	>100	>100	>100	>100	>100	>100
20.0	64.4	>100	>100	>100	>100	>100	>100	>100
22.5	38.3	76.7	>100	>100	67.8	>100	>100	>100
25.0	23.7	47.4	>100	>100	38.6	77.1	>100	>100
27.5	15.5	30.9	77.3	>100	22.0	44.1	>100	>100
30.0	10.8	21.7	54.1	>100	12.8	25.5	63.8	>100
				C/N_0 = 54.0 dB-Hz				
17.5	>100	>100	>100	>100	>100	>100	>100	>100
20.0	>100	>100	>100	>100	>100	>100	>100	>100
22.5	76.5	>100	>100	>100	>100	>100	>100	>100
25.0	47.3	94.7	>100	>100	76.9	>100	>100	>100
27.5	30.9	61.9	>100	>100	44.0	87.9	>100	>100
30.0	21.6	43.2	>100	>100	25.5	50.9	>100	>100
				C/N_0 = 57.0 dB-Hz				
17.5	>100	>100	>100	>100	>100	>100	>100	>100
20.0	>100	>100	>100	>100	>100	>100	>100	>100
22.5	>100	>100	>100	>100	>100	>100	>100	>100
25.0	>100	>100	>100	>100	94.4	>100	>100	>100
27.5	87.7	>100	>100	>100	61.6	>100	>100	>100
30.0	35.4	70.8	>100	>100	35.4	70.8	>100	>100

Table 10. Percentages of Available EIRP from 1/4 Transponder, INTELSAT Hemispheric Beam Coverage Satellite, Required to Provide Indicated Numbers of Circuits (Duplex Telephone) for C/N_0=48.0, 51.0, 54.0, and 57.0 dB-Hz and Remote Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K in a Single Channel per Carrier (SCPC) Application

	MESH Network				STAR Network			
No. of Circuits	10	20	50	100	10	20	50	100
Remote Earth Station G/T (dB/K)			C/N_0 = 48.0 dB-Hz					
17.5	59.9	>100	>100	>100	31.1	62.3	>100	>100
20.0	33.7	67.5	>100	>100	18.1	36.2	90.5	>100
22.5	19.1	38.1	95.3	>100	10.8	21.5	53.8	>100
25.0	10.8	21.6	54.0	>100	6.6	13.2	33.1	66.2
27.5	6.2	12.3	30.8	61.5	4.3	8.6	21.5	43.0
30.0	3.5	7.1	17.7	35.4	3.0	6.0	15.0	30.0
			C/N_0 = 51.0 dB-Hz					
17.5	>100	>100	>100	>100	62.1	>100	>100	>100
20.0	67.3	>100	>100	>100	36.1	72.2	>100	>100
22.5	38.0	76.0	>100	>100	21.5	42.9	>100	>100
25.0	21.5	43.1	>100	>100	13.2	26.4	66.0	>100
27.5	12.3	24.6	61.4	>100	8.6	17.2	42.9	85.8
30.0	7.1	14.1	35.3	70.6	6.0	12.0	29.9	59.8
			C/N_0 = 54.0 dB-Hz					
17.5	>100	>100	>100	>100	>100	>100	>100	>100
20.0	>100	>100	>100	>100	72.0	>100	>100	>100
22.5	75.9	>100	>100	>100	42.8	85.6	>100	>100
25.0	43.0	85.9	>100	>100	26.4	52.7	>100	>100
27.5	24.5	49.0	>100	>100	17.1	34.2	85.6	>100
30.0	14.1	28.2	70.5	>100	11.9	23.8	59.6	>100
			C/N_0 = 57.0 dB-Hz					
17.5	>100	>100	>100	>100	>100	>100	>100	>100
20.0	>100	>100	>100	>100	>100	>100	>100	>100
22.5	>100	>100	>100	>100	85.4	>100	>100	>100
25.0	85.7	>100	>100	>100	52.6	>100	>100	>100
27.5	48.9	97.7	>100	>100	34.2	68.3	>100	>100
30.0	28.1	56.2	>100	>100	23.8	47.6	>100	>100

Table 11. Percentages of Available EIRP from 1/4 Transponder, Palapa A Satellite, Required to Provide Indicated Numbers of Circuits (Duplex Telephone) for C/N_o=48.0, 51.0, 54.0, and 57.0 dB-Hz and Remote Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K in a Single Channel per Carrier (SCPC) Application

	MESH Network				STAR Network			
No. of Circuits	10	20	50	100	10	20	50	100
Remote Earth Station G/T (dB/K)				C/N_o = 48.0 dB-Hz				
17.5	9.6	19.2	47.9	95.8	5.0	10.1	25.1	50.2
20.0	5.4	10.9	27.2	54.3	3.0	5.9	14.8	29.5
22.5	3.1	6.2	15.5	31.1	1.8	3.6	8.6	17.9
25.0	1.8	3.6	9.0	18.0	1.1	2.3	5.7	11.4
27.5	1.1	2.1	5.3	10.6	0.8	1.5	3.8	7.7
30.0	0.7	1.3	3.2	6.5	0.6	1.1	2.8	5.6
				C/N_o = 51.0 dB-Hz				
17.5	19.1	38.2	95.5	>100	10.0	20.1	50.1	>100
20.0	10.8	21.7	54.2	>100	5.9	11.8	29.5	58.9
22.5	6.2	12.4	31.0	62.0	3.6	7.1	17.9	35.7
25.0	3.6	7.2	18.0	35.9	2.3	4.5	11.3	22.7
27.5	2.1	4.2	10.6	21.2	1.5	3.1	7.7	15.3
30.0	1.3	2.6	6.5	12.9	1.1	2.2	5.6	11.2
				C/N_o = 54.0 dB-Hz				
17.5	38.1	76.2	>100	>100	20.0	40.0	>100	>100
20.0	21.6	43.3	>100	>100	11.8	23.5	58.8	>100
22.5	12.4	24.7	61.8	>100	7.1	14.3	35.6	71.3
25.0	7.2	14.3	35.8	71.6	4.5	9.1	22.6	45.3
27.5	4.2	8.5	21.1	42.3	3.1	6.1	15.3	30.6
30.0	2.6	5.2	12.9	25.8	2.2	4.5	11.2	22.3
				C/N_o = 57.0 dB-Hz				
17.5	76.0	>100	>100	>100	39.9	79.8	>100	>100
20.0	43.2	86.3	>100	>100	23.5	46.9	>100	>100
22.5	24.7	49.3	>100	>100	14.2	28.4	71.1	>100
25.0	14.3	28.6	71.5	>100	9.0	18.1	45.2	90.3
27.5	8.4	16.9	42.2	84.3	6.1	12.2	30.5	61.1
30.0	5.1	10.3	25.7	51.4	4.5	8.9	22.3	44.6

The traffic analysis methodology requires knowledge or computed information to define the offered traffic load[1] for each earth station. A computed, offered load is dependent upon the number of telephones served by the earth station and the average time the telephones are used during the busy hour which is a term defined by the CCITT (1964) to designate that hour during the day when the average traffic density is the greatest. It is assumed that during the busy hour the density of traffic is fairly constant. The distribution of call lengths is assumed to be exponential with some mean value termed the mean holding time. Table 12 shows computed values of offered traffic loads for three assumed values of mean holding time--3 min, 6 min, and 10 min--and for assumptions of ten and twenty telephones served by the earth station. More discussion of the Erlang unit and details of computing offered traffic loads are given in Appendix E.

Table 12. Offered Traffic Load (in Erlangs) per Earth Station as a Function of Mean Holding Time and Number of Subscribers (Telephones) per Earth Station Assuming an Average of One Call per Two Hours per Subscriber (Telephone)

Number of Subscribers per Earth Station	Mean Holding Time (min)		
	3	6	10
10	0.25 Erl	0.50 Erl	0.83 Erl
20	0.50 Erl	1.00 Erl	1.67 Erl

---

[1] Traffic load or density is expressed in Erlangs (Erl), named after A. K. Erlang (1878-1929), the founder of telephone traffic theory. The Erlang is defined in Federal Standard 1037 (1980):

> An international (dimensionless) unit of the average traffic intensity (occupancy) of a facility during a period of time, normally a busy hour. The number of erlangs is the ratio of the time during which a facility is occupied (continuously or cumulatively) to the time this facility is available for occupancy.

We see, then, that aggregated traffic on a circuit of one call-second per second, one call-minute per minute, one call-hour per hour, etc. constitutes a traffic density (or intensity) of 1 Erl for that unit of time.

Knowing the offered traffic load, we use telephone traffic theory design tables -- such as those tables published by Siemens (1974) -- to determine the number of circuits that are required to achieve a desired grade of service. We first must make some assumptions, as follows, about the network handling of traffic in order to select the proper tables and read from the tables the desired information.

- Any attempted call which is rejected, or blocked, because there is no available circuit, is lost and causes no traffic load to any other part of the system. That is, the network operates as a loss system.
- When a subscriber offers a call, there is some probability that his call will be rejected, or blocked (lost). This probability is called the loss probability or blocking probability. The numerical value is equal to the proportion of offered calls that are rejected. Loss probability is a parameter of the traffic theory tables (and this analysis).
- Offered traffic is assumed to experience no blocking due to limitations or architecture of the switching network. This condition is termed full availability.
- The number of subscribers (telephones) serviced by the earth station is finite. (We have assumed numbers of 10 and 20.)
- Call holding times, during the busy hour, are distributed exponentially, and mean holding times are used to compute offered traffic load, as discussed above. (We have assumed mean holding times of 3 min, 6 min, and 10 min.)

Using the offered traffic loads shown in Table 12 and loss (or blocking) probabilities of 1%, 2%, and 5%, we find from traffic theory tables (Siemens, 1974) the number of circuits required (providing duplex telephony) as a function of the offered traffic load and desired grade of service. These numbers are shown in Table 13. We see that three circuits per earth station will support a rather wide range of conditions characterizing the grade of service.

The number of circuits that can be supported in MESH and STAR networks by the EIRP available from 1/4 transponder are shown in Tables 7 and 8. From Table 13 we see that three circuits per earth station will support traffic ranging from 0.25 Erl with 1% loss probability (for ten subscribers per earth station with mean holding time of 3 min) to 1.00 Erl with 5% loss probability (for 20 subscribers per earth station with mean holding time of 6 min). We use this value (three circuits per earth station) and information from Tables 7 and 8 to plot curves, parametric in required carrier-to-noise power density, which show the number of earth stations possible in a network as a function of the receiving system figure of merit (G/T), assuming 1/4 transponder is used for the space resource. Figures 8 and 9 show these curves for an INTELSAT global beam coverage 1/4 transponder and MESH and STAR network assumptions, respectively. A complete set of these curves for the parameters assumed in this analysis is provided in Appendix E. If the required carrier-to-noise power density is 54.0 dB-Hz and earth stations with G/T = 25.0 dB/K are used, we observe there could be four stations in a MESH network and seven stations in a STAR network. If a voice encoding technique were used which would provide satisfactory service with C/N_0 = 51.0 dB-Hz, then a MESH network could include eight earth stations and a STAR network could have 14 earth stations.

Table 13. Required Numbers of Circuits to Support the Offered Traffic Loads Shown (in Erlangs per Earth Station, from Table 12) for Loss (or Blocking) Probabilities of 1%, 2%, and 5%

Offered Traffic Load Erlangs/Earth Station*		Loss (Blocking) Probability		
		1%	2%	5%
0.25	(10,3)	3	2	2
0.50	(10,6) (20,3)	3	3	3
0.83	(10,10)	4	4	3
1.00	(20,6)	4	4	3
1.67	(20,10)	6	5	4

*Numbers in parentheses identify the number of subscribers, first number, and mean holding time in minutes, second number, used in computing the offered traffic load. (Refer to Table 12.)

4. CHARACTERISTICS AND COSTS OF STATE-OF-THE-ART COMPONENTS AND SYSTEMS

As a general comment, there are not many manufacturers of earth-station components and systems who seem to be seriously interested in investing in prospective applications involving INTELSAT satellites for which the earth station antenna would be smaller than 10.0 m and the system figure-of-merit design objective

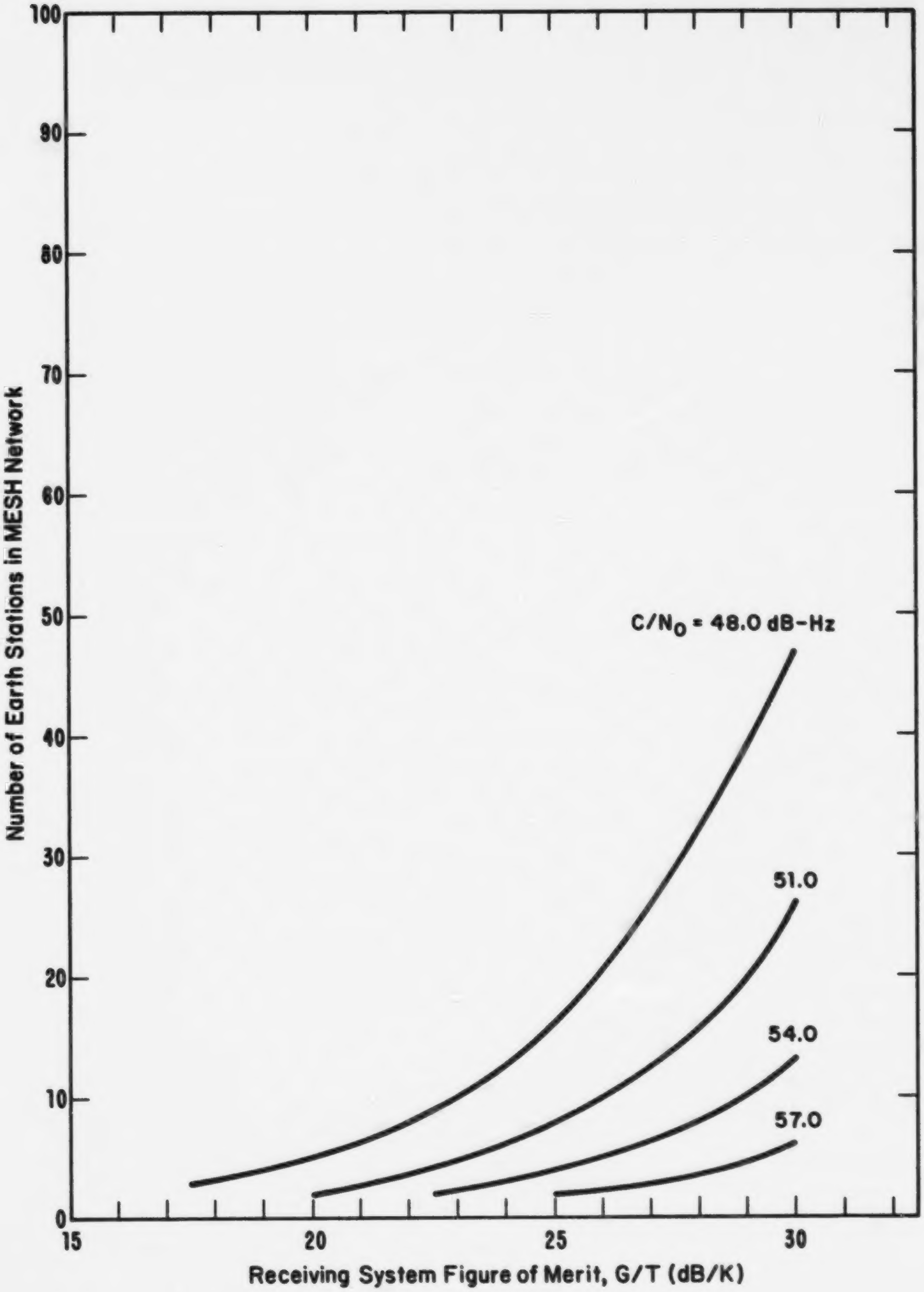

Figure 8. Curves parametric in required C/N_0 and a function of G/T showing the number of earth stations that can be supported in a MESH network by 1/4 transponder on an INTELSAT global beam coverage satellite when three circuits are provided at each earth station.

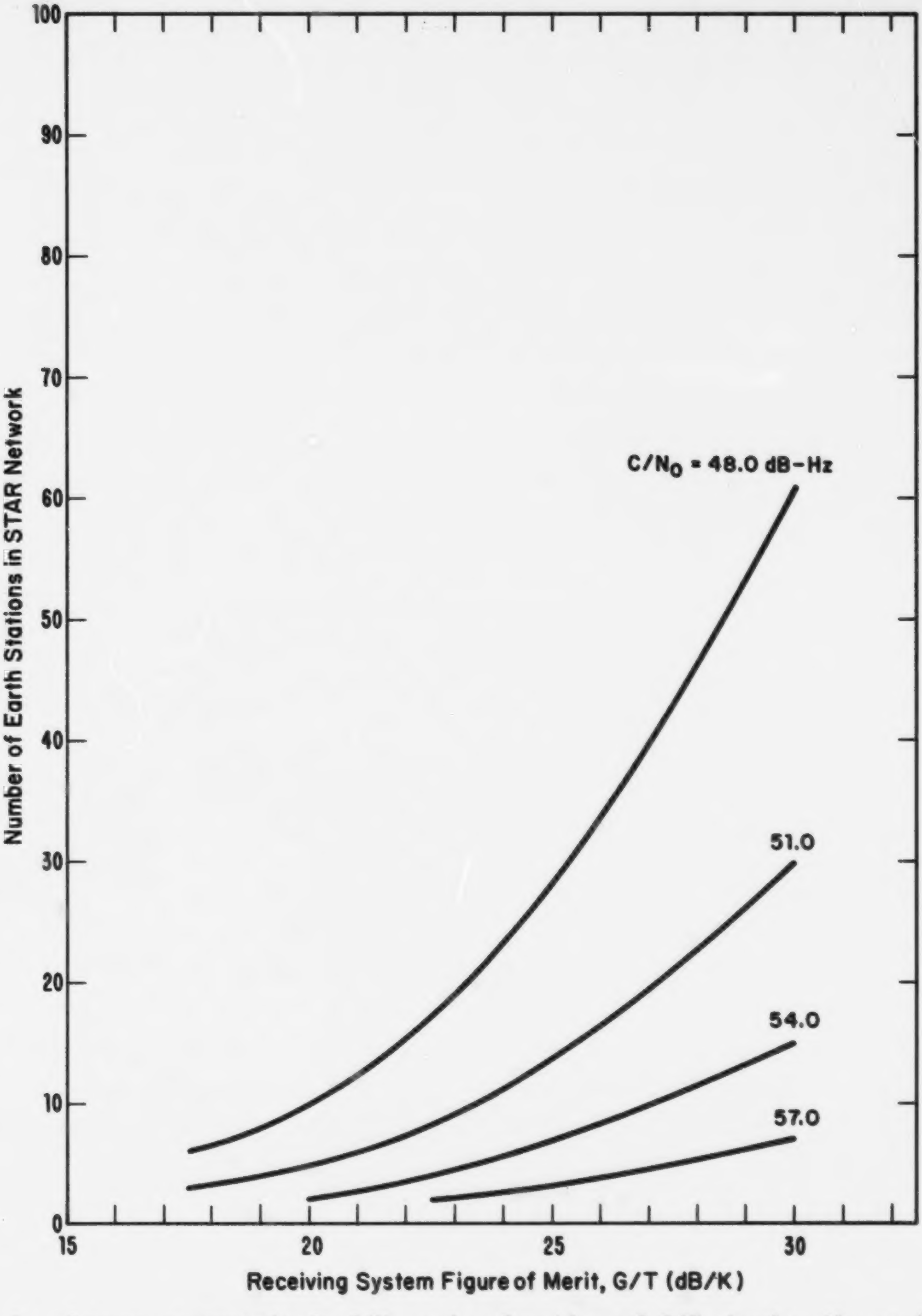

Figure 9. Curves parametric in C/N_0 and a function of G/T showing the number of earth stations that can be supported in a STAR network by 1/4 transponder and an INTELSAT global beam coverage satellite when three circuits are provided at each earth station. The central station of the STAR network is assumed to be an INTELSAT Standard B or equivalent capability earth station.

would be much less than an INTELSAT Standard B system (for which G/T = 31.7 dB/K). This attitude by manufacturers is the result of two primary factors.

The first factor is that INTELSAT policy has not encouraged the development of domestic satellite systems using leased transponder resources prior to the recently announced positions regarding leased use of INTELSAT transponder resources (Kelly, 1978, 1980; INTELSAT, 1981). This former policy resulted in little market demand for earth station components and systems in the category of low cost and small antenna apertures capable of operating (admittedly at reduced efficiency) in and with the INTELSAT system. With little market demand, there has been little development of products for such applications. For example, in a recent private communication with a representative of a firm reported to be doing 70% of the business in building INTELSAT-type earth stations, the representative commented that these special applications require case-by-case approval by INTELSAT, and he thought his firm would not be very interested in these kinds of applications. The comments were in response to questions about small earth stations operating with an INTELSAT satellite.

The second factor is the rapid growth of domestic satellite systems in the United States and the accompanying demands for and proliferation of earth stations to operate with these domestic satellites in providing new services. This demand for earth stations is so great that manufacturers are developing selective marketing policies. Examples of these selective marketing policies are a recently announced decision by a major manufacturer to not build INTELSAT-type earth stations and a private communication with a representative of another firm who stated a company policy is to market only systems and not components.

Nevertheless, there are technology and policy developments which are encouraging to the realization of satellite systems for thin-route applications using INTELSAT and other satellite resources. Previous sections of this report have discussed the INTELSAT actions taken to encourage use of leased INTELSAT transponder resources for domestic system applications. Subsequent sections of the report discuss some of the technology developments which should encourage development of systems for thin-route applications.

4.1 Antennas

The explosive demands for domestic satellite services have contributed to substantial efforts in the development of low-cost, small-aperture antennas. There are many manufacturers who offer antennas in the 3.0- to 5.0-m diameter range for simultaneous transmit and receive applications with linearly polarized feeds. Such antenna systems will operate with domestic and regional satellite systems, like Palapa, but not with an INTELSAT satellite which requires circular polarization. These domestic and regional satellite systems which provide satellite antenna coverage to relatively small areas (much smaller than the global or hemispheric coverages provided by INTELSAT satellites) have the accompanying advantage of much higher EIRP (for the coverage area) from the satellite (as shown in Section 2.1 and Appendix B); hence, the small antennas work well while still providing relatively efficient service. Catalogs and technical brochures from most of the major manufacturers state that antennas in the 3.0- to 5.0-m diameter range are available for circular polarization applications. However, personal and/or telephone contacts have verified that few units, for operation with circular polarization have been manufactured, because there has been little demand.

The principal reasons for exploring market offerings of antennas in the 3.0- to 5.0-m aperture diameter are twofold. One expects smaller antennas to be less expensive than larger antennas (though minimizing antenna cost does not necessarily minimize the total earth-station cost). Secondly, antennas in the 3.0- to 5.0-m size range are considerably easier and less expensive to transport and install than are the larger aperture (for example, 6.0- or 8.0-m diameter) antennas.

Prime focus as well as Cassegranian type feeds are used for these antennas, primarily dependent upon the development choices of the manufacturers. It does appear that slightly better performance (higher on-axis gain and lower sidelobes in the off-axis regions of the pattern) is realized with the Cassegranian type feed. One manufacturer reports development work on an offset feed design expected to produce high on-axis gain and very low sidelobe levels in the pattern to about 20° off boresight axis. No expected availability date for this antenna could be established. Though this same manufacturer minimized the cost impact of providing circular polarization, it generally was found that circular polarization added $5,000 to $10,000 to the expected antenna cost.

Certainly antenna cost is related to antenna size; however, costs for antennas (including the reflector, feed assembly, and adjustable, but manual, positioning mount) in the 3.0- to 5.0-m diameter range of size were more dependent on manufacturer and the number per order (and the type of polarization required, as discussed above) than size. Costs range from about $7,000 to $10,000 with linear polarization. One estimate of expected cost was targeted at about $5,000.

While antenna cost is directly related to antenna size, total earth-station cost likely would not be minimized by using the smallest antenna. Reference to the link budgets in Appendix D will show that use of small antennas can result in the necessity to use very large transmitter powers (high-power amplifiers), particularly for INTELSAT satellites. Cost for the high-power amplifier could then dominate the earth-station cost. Furthermore, from a technical point of view, use of high power HPA's may be impossible in many instances as a consequence of restriction to the off-axis uplink EIRP. The restriction for operation in the INTELSAT system is that off-axis EIRP must not exceed 42-25 log θ dBW per 40 KHz, where θ is the angle in degrees from the boresight axis of the antenna. In general terms, this restriction limits the HPA size to about 10W per voice channel. Costs for high power amplifiers are discussed in Section 4.3.

Examination of the link budgets for applications involving an INTELSAT satellite leads to a conclusion that 6.0-m antennas may be about the minimum practical size for such applications. Manufacturers do not offer antennas in the size range of 6.0 to 8.0 m in diameter as commonly as in the smaller sizes we have just discussed. Several reasons contribute to reduced offerings by manufacturers in this size range. First, antennas of this size, at least as we approach 8.0 m, are rather large antennas for use with domestic satellites; therefore, the demand by that market is substantially less than for the smaller antennas. Second, the international market for these sizes to be used in the INTELSAT system is not great because earth stations using these antenna sizes still will not provide a Standard B capability, i.e. $G/T \geq 31.7$ dB/K. The development of domestic systems (using INTELSAT satellite resources) where these antenna sizes are used is still in its infancy, though such development has begun. Third, antennas of about 6.0 m represent a size limit in terms of ease in transporting and installing the antenna. As mentioned earlier, antennas smaller than 6.0 m are relatively easy to transport and can be installed manually by two to four men. Antennas that are 7.0 or 8.0 m in diameter certainly are more difficult and expensive to transport and install. For example, a crane must be used during erection of the antenna. In addition, for A.I.D. application areas, the requirement for a substantial foundation and supporting structure to provide pointing stability imposes considerable difficulty and cost for transporting materials and personnel to sites, and creates a need for skilled labor at the installation site.

Some 6.0-m antenna designs may require a crane for erection, while other designs may allow manual erection of the antenna. The extremes of this situation are illustrated by two examples. One manufacturer of 6.0-m antennas uses all-aluminum reflectors and a steel pedestal. These antennas are heavy and very expensive. An antenna supplied with a circularly polarized feed (one which is INTELSAT V compatible, implying 0.5-dB axial ratio, suitable for frequency reuse applications) is reported to cost about $60,000. Another manufacturer of 6.0-m antennas uses metalized plastic reflectors and a novel design which would make transportation much easier and manual installation possible. This design is based on a three-section, 5.0-m antenna which has four quarter sections added to the circumference to make a 6.0-m antenna. Cost for this antenna with circularly polarized, INTELSAT V compatible feed is targeted at about $11,000. We believe this target is ambitious but possible, perhaps escalating to $15,000, for expected A.I.D. applications. The costs of antennas from other manufacturers in the range of 6.0 to 8.0 m in diameter fall between the extremes just discussed, tending, however, to be in the range of $35,000 to $50,000.

Earth stations with 10.0-m antennas are likely to have figures of merit near that for an INTELSAT Standard B earth station (i.e., G/T = 30 dB/K compared with 31.7 dB/K for Standard B). Hence, the cost for a 10.0-m antenna will be about $100,000. It may be necessary to install an earth station of this quality to be the central earth station in a STAR network of much smaller, remote earth stations. Otherwise, earth stations with 10.0-m antennas really should not be considered in the context of "small antenna" earth stations suitable for thin-route applications -- the subject of this report.

Figure 10 is a plot of sampled information showing the approximate relationship between antenna aperture size and antenna system (reflector, feed assembly, and mount) cost FOB the manufacturer's plant. The type of feed assembly (linear polarization, circular polarization but not INTELSAT V compatible, or circular polarization which is INTELSAT V compatible) can have significant impact on the cost of small earth station antennas.

4.2 Low-Noise Amplifiers

A full discussion of low-noise amplifier technology would consider parametric amplifiers, both cooled and uncooled, as well as GaAs FET amplifiers. However, this section discusses only the GaAs FET amplifier technology. Parametric amplifiers are very much more expensive than GaAs FET amplifiers, and the GaAs FET amplifier technology is approaching a point where the operating characteristics are suitable for most small-earth-station requirements.

Wells (1978) reported a noise temperature of 100K as about the state-of-the-art limit for FET amplifiers. Today that limit has been reduced to about 80K.

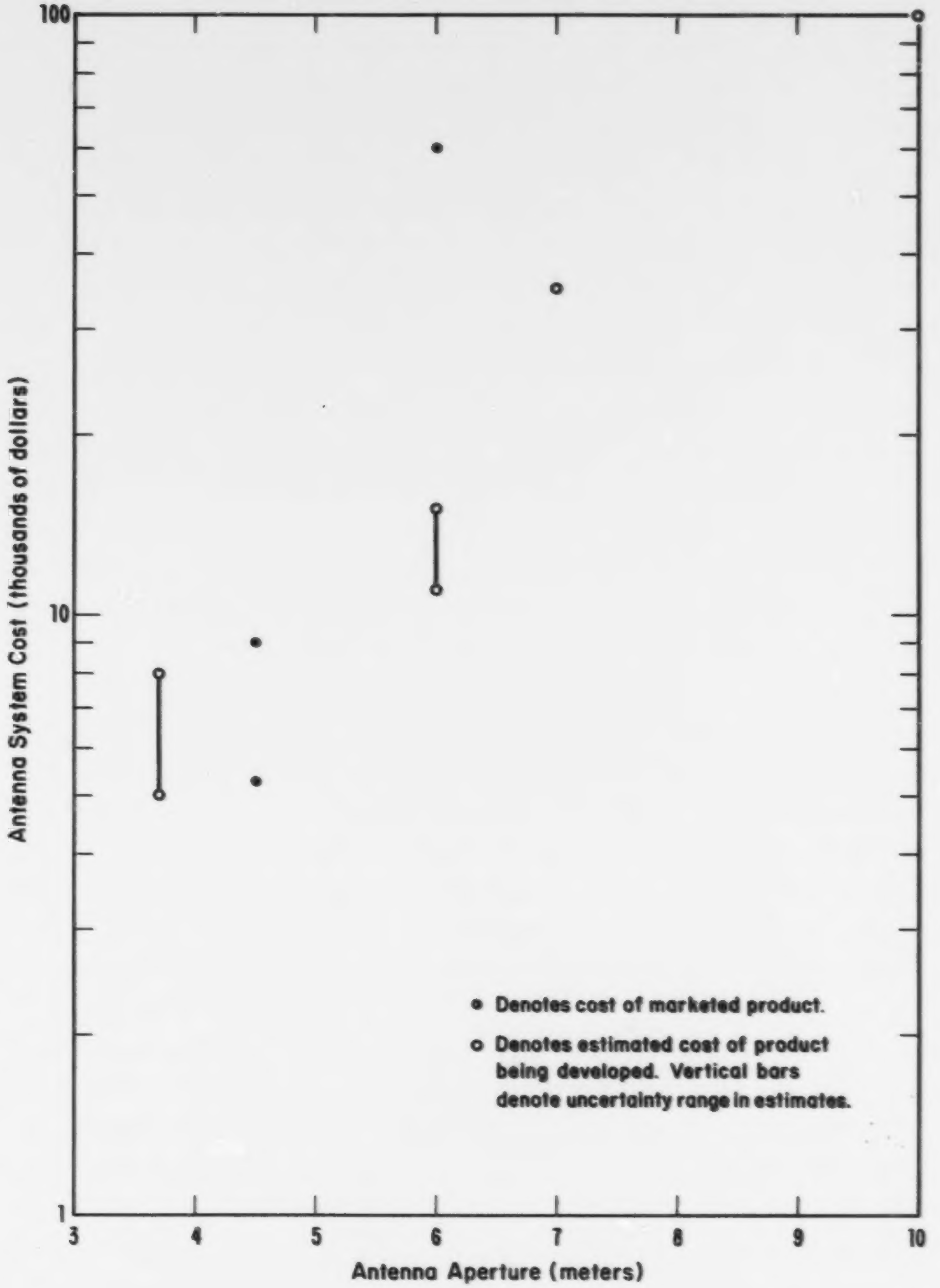

Figure 10. Sampled costs of antenna systems (reflector, feed assembly, and mount), FOB manufacturer's plant, as a function of antenna aperture size.

However, the cost does escalate sharply as this lower limit is approached. The more common noise temperatures for GaAs FET low-noise amplifiers being used today are in the range of 90K to 120K. Over this noise temperature range, costs typically are about $2,000 for 90K amplifiers down to less than $1,000 for 120K amplifiers.

Gain for these amplifiers typically is about 50 dB. Amplifiers are available with gain of 50 dB minimum and noise temperature of 80K, but the cost is about $3,000 per unit. Manufacturers today typically offer LNA's with gain that is 15 to 20 dB higher and noise temperatures that are 20K lower than were available at the time Wells (1978) made his survey. Furthermore, today's GaAs FET amplifiers (in the noise temperature range of 90 to 120K) cost only about one-third as much as in 1978. A market sample of information showing the relationship between LNA noise temperature and amplifier cost is plotted in Figure 11.

With these changes in the characteristics and costs for GaAs FET amplifiers, one should expect that considerable competition in the market has occurred. Our discussions with manufacturers and users have suggested a comment of caution because of this competition. We understand there may be substantial variations in reliability and delivery times (sometimes optimistically quoted) as well as cost. A potential buyer needs to make a careful survey not only of the market suppliers, but also of other recent buyers and their experiences.

4.3 High Power Amplifiers

This section looks both at the traveling wave tube amplifier (TWTA) market and the developing GaAs FET power amplifier market. A caution similar to that expressed for the low-noise amplifier market is appropriate for the TWTA market, where there also is considerable competition.

There are TWTA products available with output powers from 10 W to kilowatts of power. We consider the range from 10 W to 400 W, which likely is more power than would be used by small earth stations in thin-route applications. Yet, 400 W may be only about "one step" beyond the upper limit of some small-earth-station HPA requirements. The relationship between output power and cost, based upon a limited but representative market sample, is shown in Figure 12.

The information shown by Figure 12 indicates little difference in cost for units with output power capacity of 40 W or less. That is, it costs about $10,000 for a TWTA with 40 W, 20 W, or even 10 W of output power. One manufacturer does offer a general purpose, instrumentation amplifier for the 4- to 8-GHz band with nominal output power of 20 W for $8,325. It was mentioned that many tested

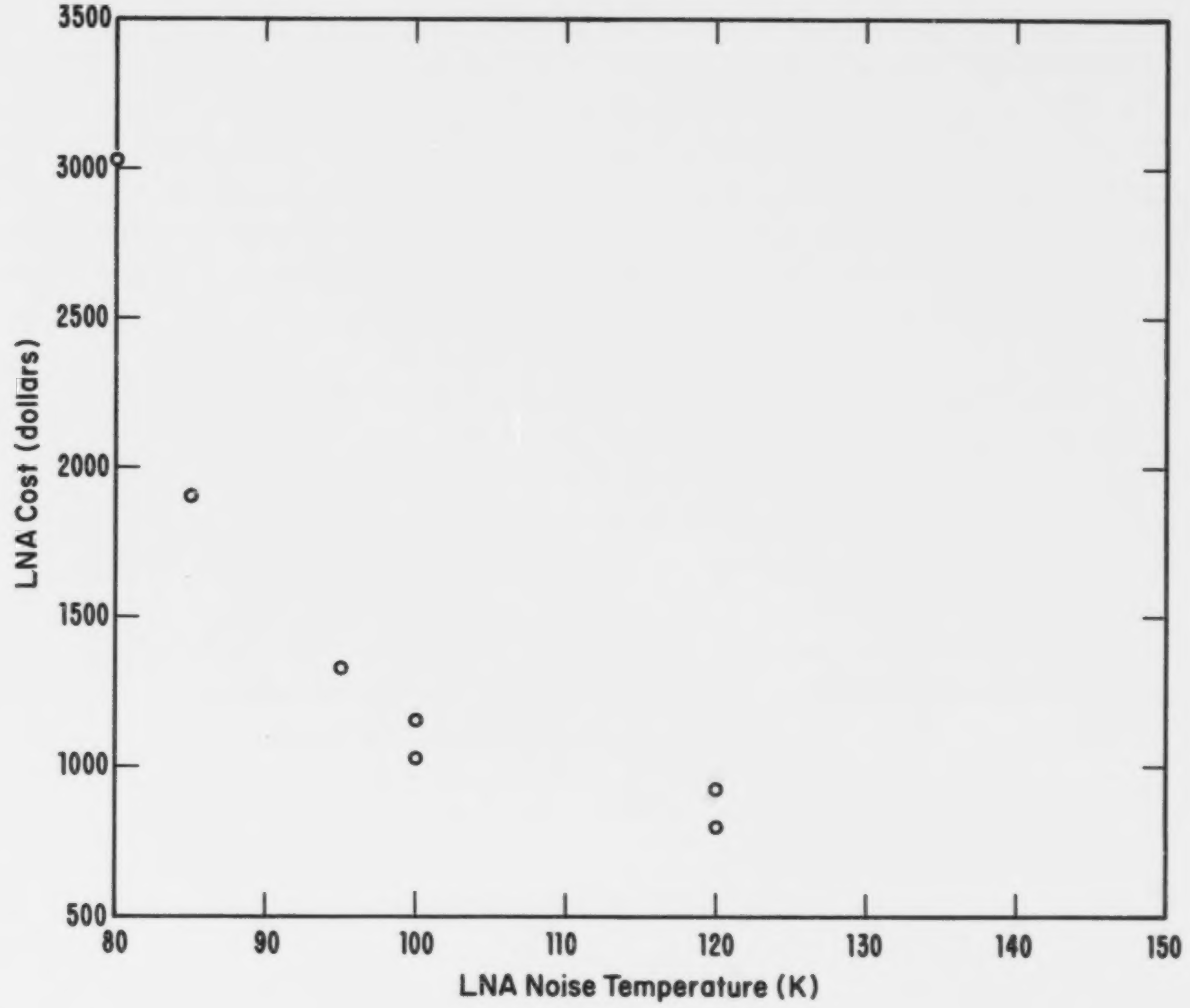

Figure 11. Sampled costs of GaAs FET low noise amplifiers which operate at 4 GHz as a function of rated amplifier noise temperature.

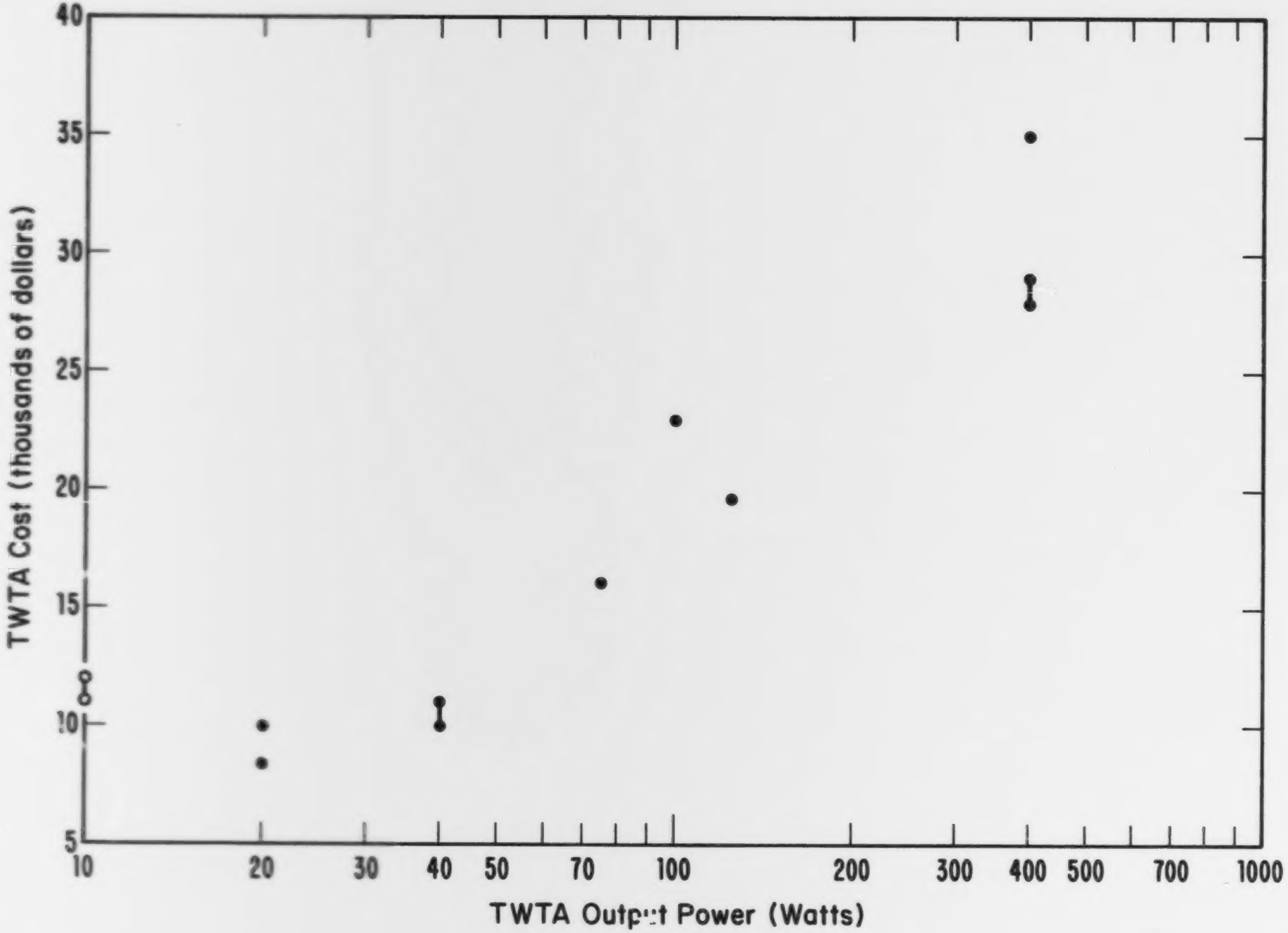

Figure 12. Sampled costs of traveling wave tube amplifiers which operate at 6 GHz for high power amplifier applications as a function of rate amplifier output power.

units have shown output power of ~30 W in the earth-station transmit band of 5.9 to 6.4 GHz.

For applications which require an output power capacity of about 100 W, the amplifiers will cost about $20,000 to $23,000, depending upon the manufacturer. The cost for 400 W of power will increase to about $30,000 to $35,000. However, it is unlikely that an earth station for a thin-route application would be allowed to operate with that much power due to the off-axis EIRP restrictions imposed by INTELSAT (and other satellite owners, as well).

The development of solid-state power amplifiers, using GaAs FET devices, likely will be very active during the next several years. Manufacturers offer 5-W linear amplifiers (with 47 dB gain) today which cost about $4,000. These 5-W amplifiers are being power combined, in response to special order requests, to achieve about 8 W output power. The projection is that 10-W linear amplifiers will enter the market in late 1982. Figure 13 portrays market sampled information of unit costs versus output power with a projection of cost for these 10-W linear amplifiers. The cost is estimated to range from $4,500 to $5,400. The vertical bars on Figure 13 indicate variation in unit cost depending on the number of amplifiers purchased. Since development of GaAs FET amplifiers is expected to be active, we expect more competition in the market to occur with a decrease in unit cost resulting. Perhaps the pattern followed by the LNA unit costs will be repeated.

4.4 Up/Down Frequency Converters

Frequency converters translate signals from the nominal 70 MHz IF to uplink radio frequencies in the 5.925- to 6.425-GHz band (upconverters) and from the downlink radio frequencies in the 3.700- to 4.200-GHz band back to IF, nominally 70 MHz (downconverters). The market offers frequency converters over a rather wide range of quality and convenience features with accompanying variations in the cost. Of course, the application ultimately dictates the minimum quality (number of conversion stages, frequency stability, phase noise, etc.), and to some extent, the convenience features (crystal tuning versus frequency synthesis with thumb-wheel switches or programmable control, sensing and alarm circuits, monitoring/test ports, etc.) which must be provided in the frequency converters.

Typical thin-route communication telephony requirements of a few channels per earth station (in Section 3.2, we have suggested three circuits per earth station as a representative capability) may be satisfied by using either SCPC-FM or some digital voice encoding technique, for example CVSD. For the

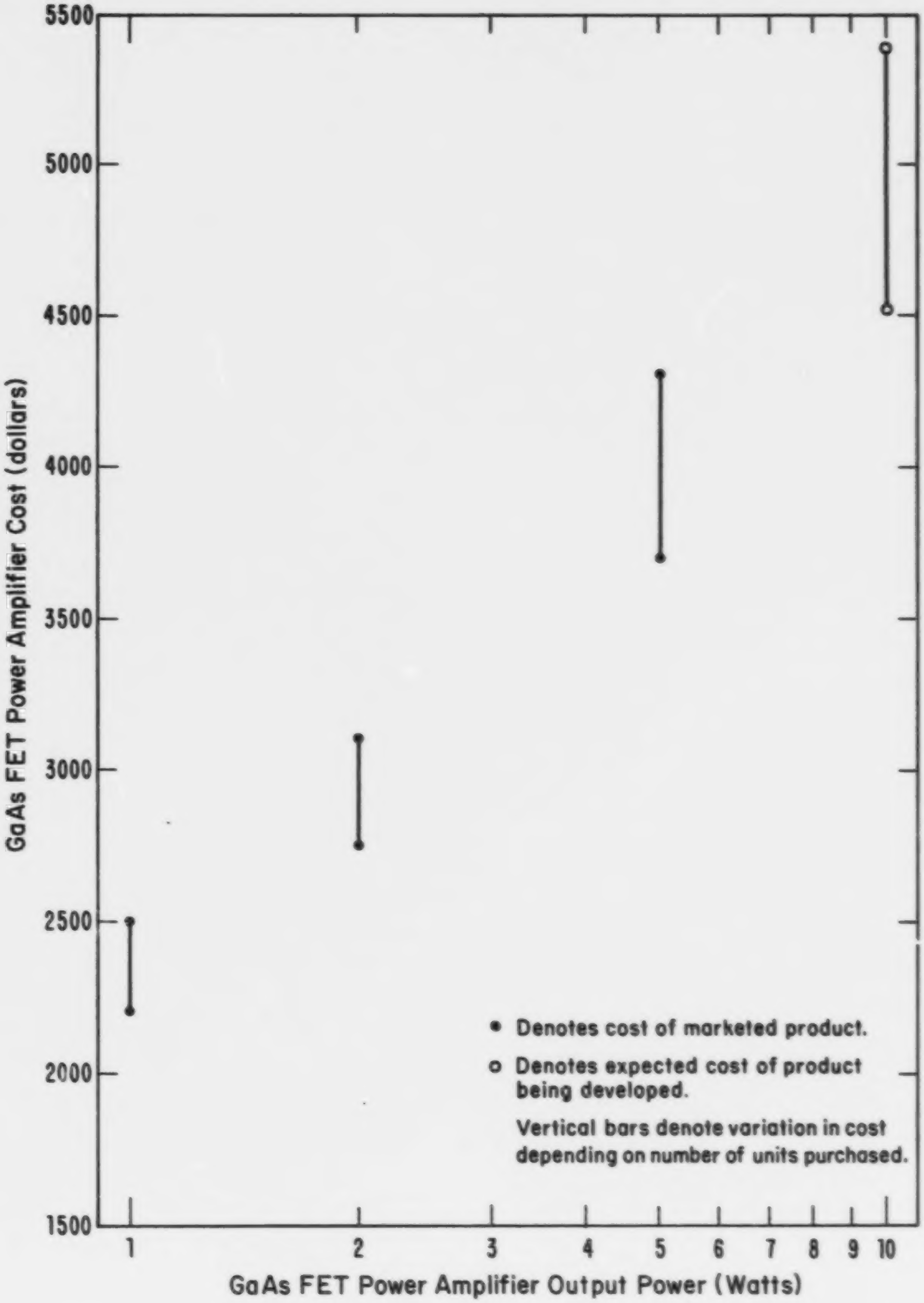

Figure 13. Sampled and estimated costs of GaAs FET amplifiers which operate at 6 GHz for power amplifier applications as a function of rated amplifier output power.

moment, consider use of a digital encoding technique. This choice would mean that the frequency converters must be of quality suitable for a small, digital, earth station. This quality also would be suitable for a few SCPC-FM channels.

Let's consider a few of the principal features for frequency converters suitable for small, digital, earth stations or SCPC-FM stations providing a few voice channels. The converters will be double conversion type units with timing provided on a local oscillator which is phase-locked for stability, probably by use of plug-in crystals with provision for six or twelve channels. The frequency stability will be about 1 part in 10^7 per month which translates to about 400 Hz/mo for the downconverter and 600 Hz/mo for the upconverter. The converters will be self-contained with respect to reference frequency and power supply requirements. There will be direct plug and signal-level compatibilities with the Modem on the IF side and the high-power amplifier (for the upconverter) and the low-noise amplifier (for the downconverter) on the rf side.

The upconverter and downconverter may be individually packaged or combined in a single, rack-mountable package for which some economies may be realized because power supplies, reference frequency oscillators, etc., may be shared. Individually packaged units will cost about $9,000 each, minimum. There are single-packaged, combined up and down converters available for $10,000 to $15,000. Costs increase from these minimum values as convenience features are added. There also will be additional costs for equipment racks and cabling. In fact, it may be advantageous to purchase specially designed racks and cable kits which may add $5,000 to $10,000 to the aggregated costs for frequency converters, Modems, and telephone channel units.

4.5 Modems and Voice Modulation Units

In earlier sections of this report we have discussed the telephone service that could be provided using either analog or some type of digital voice encoding technology. The types of equipments required to implement each technology are quite different, therefore separate discussions are given. Each subsection discusses all the equipment required between a telephone handset (or the switching and distribution network which might connect several handsets) on one side and the frequency converters on the other (IF) side.

4.5.1 Analog Technology (SCPC-FM)

Telephone service provided with analog technology would employ SCPC-FM, which is by far the most common type of service equipment in use today. Figure 14 is a block diagram of the baseband, signaling, and IF equipment for an SCPC-FM application. This figure expands the blocks labeled CHANNEL EQUIPMENT and

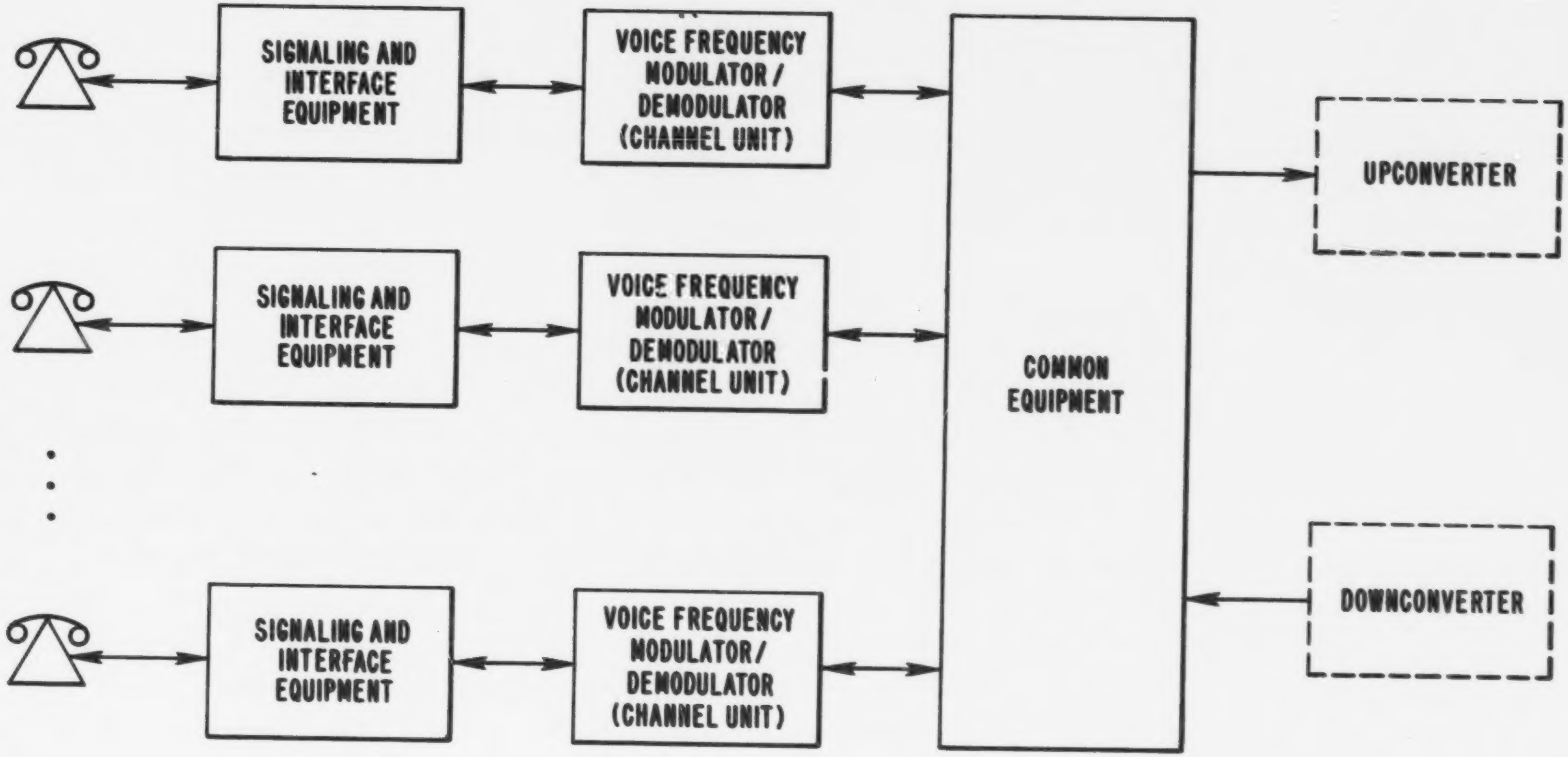
SIGNALING AND INTERFACE EQUIPMENT
VOICE FREQUENCY MODULATOR/ DEMODULATOR (CHANNEL UNIT)
SIGNALING AND INTERFACE EQUIPMENT
VOICE FREQUENCY MODULATOR/ DEMODULATOR (CHANNEL UNIT)
SIGNALING AND INTERFACE EQUIPMENT
VOICE FREQUENCY MODULATOR/ DEMODULATOR (CHANNEL UNIT)
COMMON EQUIPMENT
UPCONVERTER
DOWNCONVERTER

Figure 14. Block diagram of the baseband, signaling, and IF equipment for SCPC-FM telephony.

CHANNEL INTERFACE EQUIPMENT in Figure 3. A telephone handset for four-wire connection could be connected directly into the voice frequency modulator/demodulator, commonly referred to as the channel unit; however, most applications will require provisions for signaling.

Signaling is a term used to describe the exchange of control information between earth stations, switching centers which may be connected to earth stations, and the users of the network. There is a broad range of network management functions that may be conducted with signaling. These functions include supervisory control and status, call address (such as would be initiated by the user with rotary or push-button "dialing"), and audible/visual information such as dial tone, busy tone, ringing, etc. (Linfield and Nesenbergs, 1978). Consideration of signaling requirements is extremely important to implementation of networks for thin-route communications, but technical considerations are extensive unto themselves and beyond the scope of this report. There are many signaling standards throughout the world and many more techniques in service. Readers, therefore, are referred to other sources such as the CCITT (1973) Green Book or Dahlbom (1977) for thorough treatments of signaling standards and techniques. Linfield and Nesenbergs (1978) present a good summary of many signaling techniques.

The voice frequency modulator/demodulator, or channel unit, accepts the voice-band, analog signals and performs frequency modulation of these signals to IF. Other processes important to frequency-modulated voice, and satellite networks, which typically are accomplished in the channel unit, include companding, pre-emphasis/de-emphasis, echo suppression, and voice operated switching (VOX) to reduce consumption of satellite power.

There are a number of necessary equipment items to support an SCPC-FM system which often are referred to as common equipment. The significant components of the common equipment include the following:

-- A master frequency generator which provides a reference frequency to each voice frequency modulator/demodulator (channel unit) and, sometimes, to the up and down frequency converters.

-- A pilot (frequency) generator (only at one earth station in the network) to provide a pilot tone reference throughout the network for determining frequency translations which have occurred in the link.

-- An automatic frequency control (AFC) unit to generate the necessary frequency translations using the pilot tone.

-- Power combiners (passive) to combine the IF signals from each channel unit (for transmission) into a single IF signal for the upconverter.

-- Power dividers (passive) to distribute the single IF signal from the downconverter to the several channel units (demodulators) incorporated into the earth station.

-- Transmit and receive amplifiers to overcome the losses occurring in the passive combiner/divider operations. These amplifiers may not be used when the station has only a few (perhaps eight or fewer) channel units.

-- The up/down frequency converters are considered by some manufacturers to be part of the common equipment.

-- Power supplies as required by the other components of common equipment.

As we consider cost, it is important to realize that a complement of common equipment is required to provide even one channel of SCPC-FM service, though the additional costs for adding a few more channels may then be small. While some manufacturers do include frequency converters as part of the common equipment for SCPC-FM systems, we have considered these equipment items separately (Section 4.4). Hence, the typical costs quoted by this report for common equipment do not include frequency converters.

We find that common equipment for an SCPC-FM system suited to thin-route applications should cost about $25,000 to $30,000 depending on the application variables mentioned above. This cost should include equipment racks and special cabling to provide plug-compatible interconnections of all the common equipment. The voice frequency modulator/demodulator units (channel units) should cost about $4,000 to $4,500 per channel. Finally, signaling and related interface equipment should cost about $2,000 to $2,500 per channel, though it should be noted that this cost is an estimate which will be subject to many variables in system implementation as discussed briefly in an earlier paragraph of this section.

4.5.2 Digital Technology

There are two types of digital technology which conceivably could be used to provide telephone service in a thin-route type of application. One technique would utilize some voice synthesis algorithm for which the predictor coefficients would be digitally encoded and transmitted at a very low data rate, for example 2400 or 4800 bps. The second technique would be a direct digital encoding of the sampled, analog waveform using an adaptive or variable slope delta modulation scheme at a relatively low sampling rate, for example 16 kbps. Figure 15 shows a block diagram of the baseband, signaling, and IF equipment required to implement a technique for digital voice encoding. A voice synthesis technique would differ only in that the handset and voice encoder probably would be a combined

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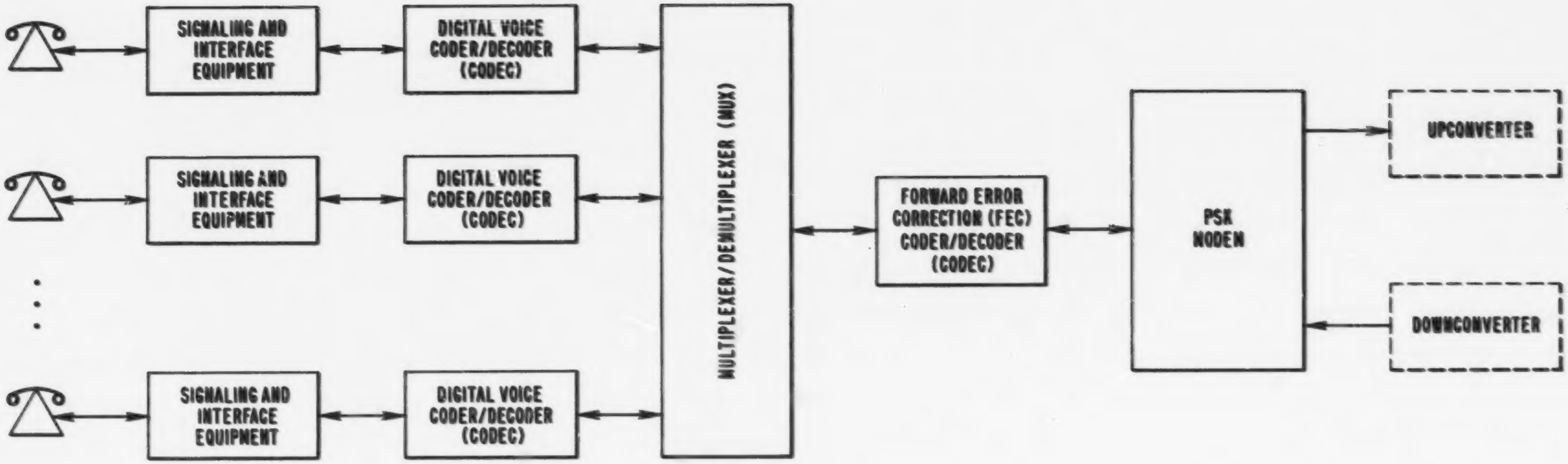

SIGNALING AND INTERFACE EQUIPMENT
DIGITAL VOICE CODER/DECODER (CODEC)
SIGNALING AND INTERFACE EQUIPMENT
DIGITAL VOICE CODER/DECODER (CODEC)
SIGNALING AND INTERFACE EQUIPMENT
DIGITAL VOICE CODER/DECODER (CODEC)
MULTIPLEXER/DEMULTIPLEXER (MUX)
FORWARD ERROR CORRECTION (FEC) CODER/DECODER (CODEC)
PSK MODEM
UPCONVERTER
DOWNCONVERTER

Figure 15. Block diagram of the baseband, signaling, and IF equipment for digitally encoded telephony.

unit, since voice synthesizing techniques often require use of special telephone hand sets. For example, the hand set may require use of a dynamic rather than carbon microphone in the mouthpiece. A replacement dynamic microphone will include a built-in amplifier for high output level, and may include noise cancelling, to provide a high fidelity audio signal.

Signaling, once again, is an important consideration in developing any thin-route communications network. Please refer to Section 4.5.1 for some general discussion of signaling. For digital telephony at encoding rates below 32 kbps, the in-band signaling tones must be converted to information contained as specific bits in a transmitted signal rather than simply encoded as part of the analog signal. This requirement can add "overhead" bits to the composite bit stream (after multiplexing). Further discussion of the technical considerations associated with signaling in the digital telephone system is beyond the scope of this report.

The accommodation of signaling requirements in any digital service application, either synthesized or waveform encoding, would require one or two printed circuit boards per telephone channel and a printed circuit board equipment module. The estimated cost for these signaling equipment items is $150 to $200 for the printed circuit board module plus about $25 per printed circuit board. In applications where at least three telephone circuits are provided at an earth station, the signaling equipment cost should not exceed $100 to $200 per channel.

The digital voice encoder/decoder equipment could apply one of several techniques. A voice synthesis application probably would use some adaptive predictive coding (APC) algorithm such as APC-4 or one of the linear predictive coding (LPC) algorithms such as LPC-10. According to Flanagan, et al. (1979) adaptive predictive coding can produce toll quality speech transmission at 16 kbps or communications quality at 7.2 kbps; however, the coder (equipment) is approximately 50 times more complex than a simple adaptive delta modulator. Flanagan, et al. (1979) do not indicate the required sampling rate for achieving toll or communications quality tramission with linear predictive coding but do report a synthetic quality transmission is provided at a coding rate of 2.4 kbps. However, the LPC equipment is reported to be 100 times more complex than a simple delta modulator. The most common uses for voice synthesis techniques are those where extreme bandwidth restrictions are imposed or secure communications are required.

Complexity of the voice synthesis techniques makes equipment quite expensive. We noted earlier that special telephones may be required. Typical cost for a telephone and voice encoder/decoder (VOCODER) unit using LPC-10 technology is about $13,000. Since APC technology is somewhat less complex, we estimate cost for a telephone and VOCODER unit using APC would be about $10,000.

Waveform encoding of voice signals is becoming a common technology application today. Many manufacturers offer equipment for this purpose, typically developed using some algorithm for continuously variable slope delta modulation (CVSD). Flanagan, et al. (1979) report required coding rates of 40 kbps for toll quality transmission and 24 kbps for communications quality transmission using adaptive delta modulation. In their paper, the term adaptive delta modulation (ADM) is used to refer generally to all types of delta modulators which employ variable (or adaptive) step size encoding as opposed to linear delta modulators which employ fixed (or nonadaptive) step size encoding of the analog signal. Many manufacturers today are reporting that very satisfactory telephone service can be provided using ADM technology at sampling rates as low as 16 kbps. Customers using the ADM technology historically have been predominantly military; however, there are growing numbers of nonmilitary users. Many of these newer users of ADM technology have communications requirements similar to typical thin-route requirements, as defined and discussed in Section 1.3.

Digital voice encoder/decoder equipment which uses sampling rates at 16 kbps or higher (as specified by a user) and which are compatible with four-wire telephones are readily available from a variety of manufacturers.

The cost for adaptive delta modulation (probably CVSD) voice encoder/decoder equipment is about $1,500 per channel plus about $800 for a tray, with power supplies, connectors, etc., which will hold printed circuit boards for up to eight channels. The CVSD encoding/decoding equipment which will accept data as well as analog input signals will cost more -- about $3,000 to $4,000 per channel.

The bit streams from several digital voice encoder/decoder units can be multiplexed into a single, composite bit stream for transmission. This feature, providing several telephone channels on a single rf carrier, may have significant implications on the cost of an earth station because single-carrier operation could reduce the power capability required of the high-power amplifier and, thus, cost. Single carrier operation would allow saturated (nonlinear) operation of the amplifier, whereas multiple-carrier operation (such as three channels of SCPC-FM telephony) would require linear (backed-off) operation of the amplifier. The composite bit rate will be about 1.05 times the sum of the separate bit rates. That is, the typical multiplexer is about 95% efficient. The maximum bit rate for the composite bit stream will be determined by the channel-spacing requirements that may be imposed by the satellite owner, for example INTELSAT. (Following discussion of the forward error correction (FEC) coder/decoder and Modem equipments, we discuss some configurations of digital baseband and IF equipment, to arrive at composite bit stream rates which establish required bandwidth and hence channel spacing, which we believe are reasonable.) A multiplexer will cost about $1,500 for up to five digitized voice inputs. The multiplexer will use printed circuit boards which may plug into the same tray used for the voice encoder/decoder boards. A complete, stand-alone multiplexer will cost about $2,000 to $2,500.

Forward error correction coding can (and should) be used to realize lower bit-error rates for a given operating carrier-to-noise power density ratio. According to Jacobs (1974) and Nesenbergs (1975), such coding can provide 6 or 7 dB actual coding gain (at carrier-to-noise power density ratios and bit-error rates typical for digital voice communications), depending on the coding techniques that are used. Convolutional coding with maximum likelihood (Viterbi) decoding is the most common. Error correction coding rates of 1/2, 3/4, and 7/8 are commonly available from manufacturers. These rates express the ratio between the number of information bits presented to the coder and the number of bits used to transfer that information, hence the redundancy in the composite bit stream. Typical cost for forward error correction coding/decoding (CODEC) equipment is about $4,500 per earth station.

Translation of baseband signals to IF would use either biphase (B) or quadra- (Q) phase shift keying (PSK) Modems. Many manufacturers offer these Modems at prices ranging from about $6,500 to $8,000. There is essentially no difference in cost for biphase or quadraphase technology. Differences in Modem costs reflect, primarily, market differences due to supplier and, secondarily, differences in convenience features (such as indicators, which may or may not be provided).

Now, consider an earth-station configuration of baseband and IF equipment which would provide three circuits of telephone service using an adaptive delta modulation at an encoding rate of 16 kbps. The composite bit rate following the multiplexer would be 48 kbps, neglecting multiplexer inefficiency. Forward error correction at rate R=3/4 will increase the composite bit rate of the baseband signal to 64 kbps. Using a QPSK modem the symbol rate would be 32 k symbols/sec. The unfiltered bandwidth which includes 99% of the average spectral energy (20-dB bandwidth) would be about 120 kHz. However, manufacturers offer band-limiting filters with 9-pole Nyquist filtering characteristics which allow channels to be spaced as close as 1.5 times the symbol-rate spacing (for example, see Gray, 1981), or 48 KHz for this example. A standard channel spacing for INTELSAT, and for other satellite systems as well, is 45 kHz. We should also remember that in thin-route applications with small-antenna earth stations, service limitation almost certainly will depend on available satellite-transponder rf power rather than available rf bandwidth. This means that the satellite transponder will not have enough power to support use of every available channel, so that perhaps only every other channel or every third channel can be used.

An alternative for this example would be to use a BPSK rather than QPSK Modem. The required symbol-rate then would be 64 k symbols/sec for which the channel spacing requirement would be 96 kHz. This channel spacing requirement would easily conform with use of every third channel in a normal 45-kHz channel-spacing plan. The possible advantage of this alternative is that uplink EIRP would be spread over a wider bandwidth, thus the off-axis uplink EIRP restriction for power not to exceed $42 - 25 \log \theta$ dBW/40 kHz (where θ is the angle in degrees from antenna boresight axis) would be satisfied more easily.

4.6 Complete Earth-Station Systems

This section discusses a complete, non-redundant earth station for thin-route applications. The earth station may be configured by the user (or a contractor for the user) using components from a variety of manufacturers with integration done by the user (or his contractor). Or the complete earth station may be purchased from a single supplier who does the system integration. Previous subsections of Section 4 have discussed the principle components of the earth station and estimated costs for those components individually. In this section, we discuss some complete (or turn-key) earth stations which are available or expected soon to be available on the market. The discussion considers significant system features and estimated costs, but specific sources are not identified. No preference, ranking, or recommendation is intended or implied by the order in which types and sizes of earth station systems are discussed. Our analysis of and recommendations for systems which will satisfy requirements for the Rural Satellite Program sponsored by the Agency for International Development are presented and discussed later in this section.

Earth stations with antennas that are 3.0 to 4.5 m in diameter are on the market, primarily as television receive-only stations or low-capacity data terminals operating with domestic satellites. These stations sell for \$20,000 to \$50,000 or more, depending on the type of application to be met. For example, U.S., domestic receive-only, television earth stations range upwards in cost from \$20,000, although earth-station kits are available for less than \$20,000. There is little likelihood that such systems could be adapted to provide satisfactory telephone service in a thin-route application using an INTELSAT satellite. All other factors aside, the cost would increase $10,000 to $15,000 for such a system which could operate with the circular polarization of INTELSAT signals. The system cost would increase even more if the system were to offer an INTELSAT V-compatible, frequency re-use antenna feed for circular polarization. (It should be noted, however, that we have found it difficult to obtain typical market costs for such systems.)

One manufacturer offers a line of digital earth terminals with antenna size ranging from 3.0 to 7.0 m which can be obtained as INTELSAT-compatible stations. This station with a 3.0 m antenna could provide up to four telephone channels, using digital voice synthesis techniques, on a single carrier per earth station. However, the power available for one-quarter transponder on an INTELSAT satellite with global beam coverage could only support about 18 rf carriers to provide 36 telephone circuits for the network. There are other serious technical problems with such an application (i.e., excessive EIRP on the uplink) which may prevent its use with an INTELSAT satellite. Furthermore, the system cost would be about $125,000 for a 3.0-m antenna, increasing to $150,000 or $175,000 for a system with a 7.0-m antenna. This manufacturer does report that company funds are budgeted in 1982 for development of a low-cost, "small international terminal."

There are a number of manufacturers who offer earth stations with 4.5- or 5.0-m antennas, primarily for operation as (digital) data terminals typically at 56 kbps or multiples of 56 kbps, with a domestic type satellite. One manufacturer is planning to offer by late 1982 a low-cost earth station, for use with domestic type satellites, which will provide two channels of SCPC-FM (duplex) telephone service. The station cost is estimated to range between $40,000 and $55,000 using a 5.0-m antenna. The manufacturers further estimated that cost would increase by about $15,000 for that earth station to operate in the INTELSAT system. One recently negotiated contract with a large manufacturer of satellite earth stations will provide a small number of earth stations using 6.0-m antennas with circularly polarized feed (not a frequency re-use type) and SCPC-FM equipment for two (expandable to four) telephone circuits per earth station at a cost slightly in excess of $200,000 per earth station.

As noted above there are a variety of manufacturers who offer digital earth stations for operation with the domestic satellites. These terminals, in a non-redundant configuration, typically cost about $60,000 to $80,000 (without equipment for digital voice encoding and circularly polarized feed for the antenna). One manufacturer projects a system of this type at $50,000 within the next year. The addition of adaptive delta modulation for voice signal encoding and MUX equipment for up to five telephone circuits would add about $10,000 to the earth-station cost. It should be noted, however, that estimates of earth-station cost really are approximate when made without considering details and influences of the application. For example, the type and capacity of the high-power amplifier that is required has a substantial impact on the earth-station cost.

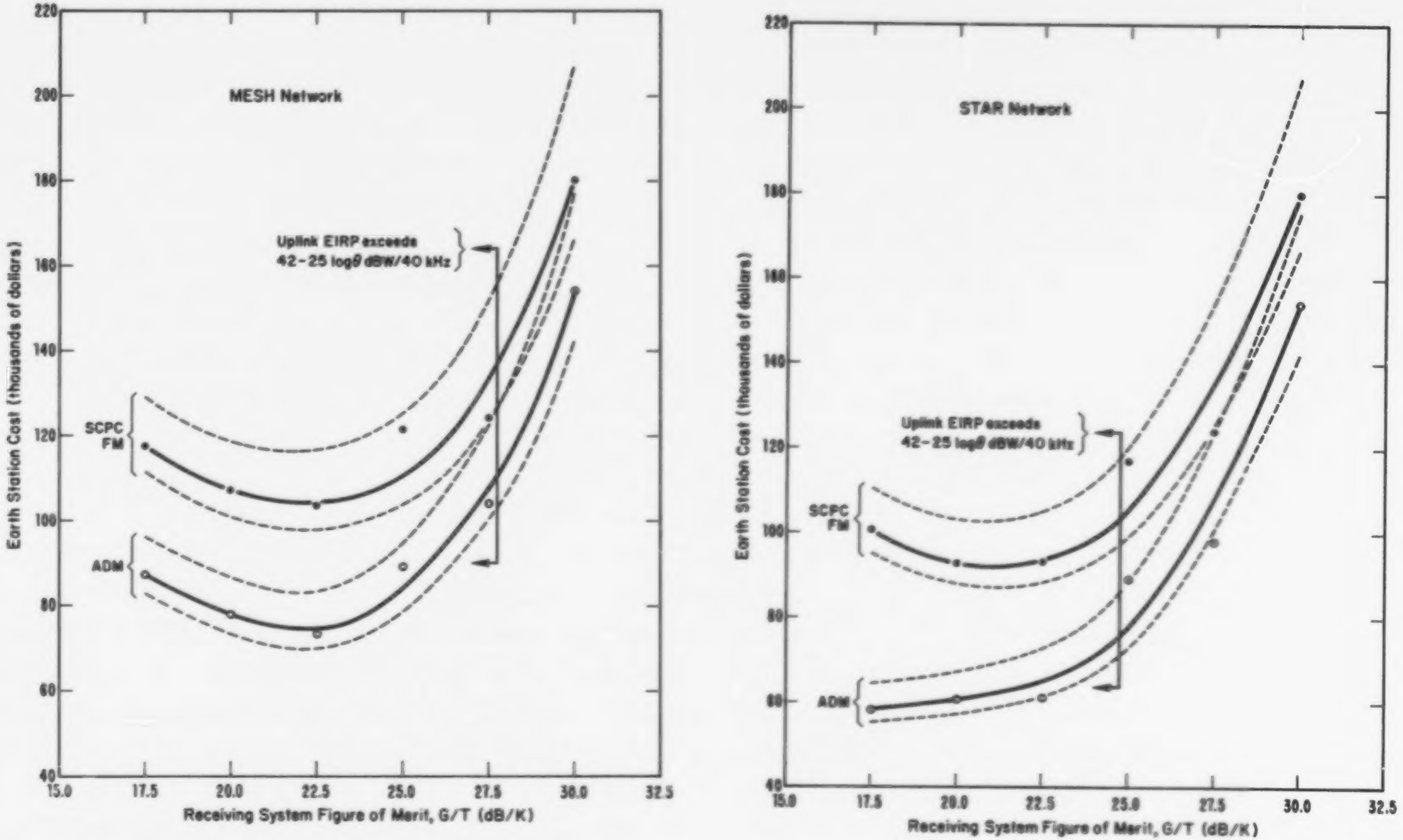
Continuing our analysis of Section 3, we assume an earth station that would provide three telephone circuits. Assuming C/N_0 = 54.0 dB-Hz, we then use the earth-station component cost information discussed in Sections 4.1 through 4.5 to estimate total earth-station cost as a function of the receiving system figure of merit (G/T). (Recall that Figure 4 relates figure of merit and low-noise amplifier temperature to antenna size.)

These estimates of cost are shown in Figures 16, 17, and 18 for INTELSAT global beam coverage, INTELSAT hemispheric beam coverage, and PALAPA satellites respectively. Each figure has two sets of curves for MESH and STAR networks, as noted. And for each type of network, there are estimated costs for service implementations using single channel per carrier, frequency modulation (SCPC-FM) or adaptive delta modulation (ADM) technology. The dashed-line curves indicate estimate uncertainties, arbitrarily selected, of +10% and -5% at G/T=17.5 dB/K increasing linearly to +15% and -7 1/2% at G/T=30.0 dB/K.

Arrowed lines also are drawn on the figures to indicate that the INTELSAT uplink EIRP restriction would be violated by an earth station of lesser capability, assuming that the reduced capability resulted from use of a smaller antenna rather than a higher system noise temperature. Of course uplink EIRP does not relate directly to receiving system figure of merit. But receiving system figure of merit and uplink EIRP, as well, do relate to antenna size, though not uniquely. Therefore, the arrowed lines must be understood as approximate indications of minimum, satisfactory, earth-station antenna size determined by reference to Figure 4.

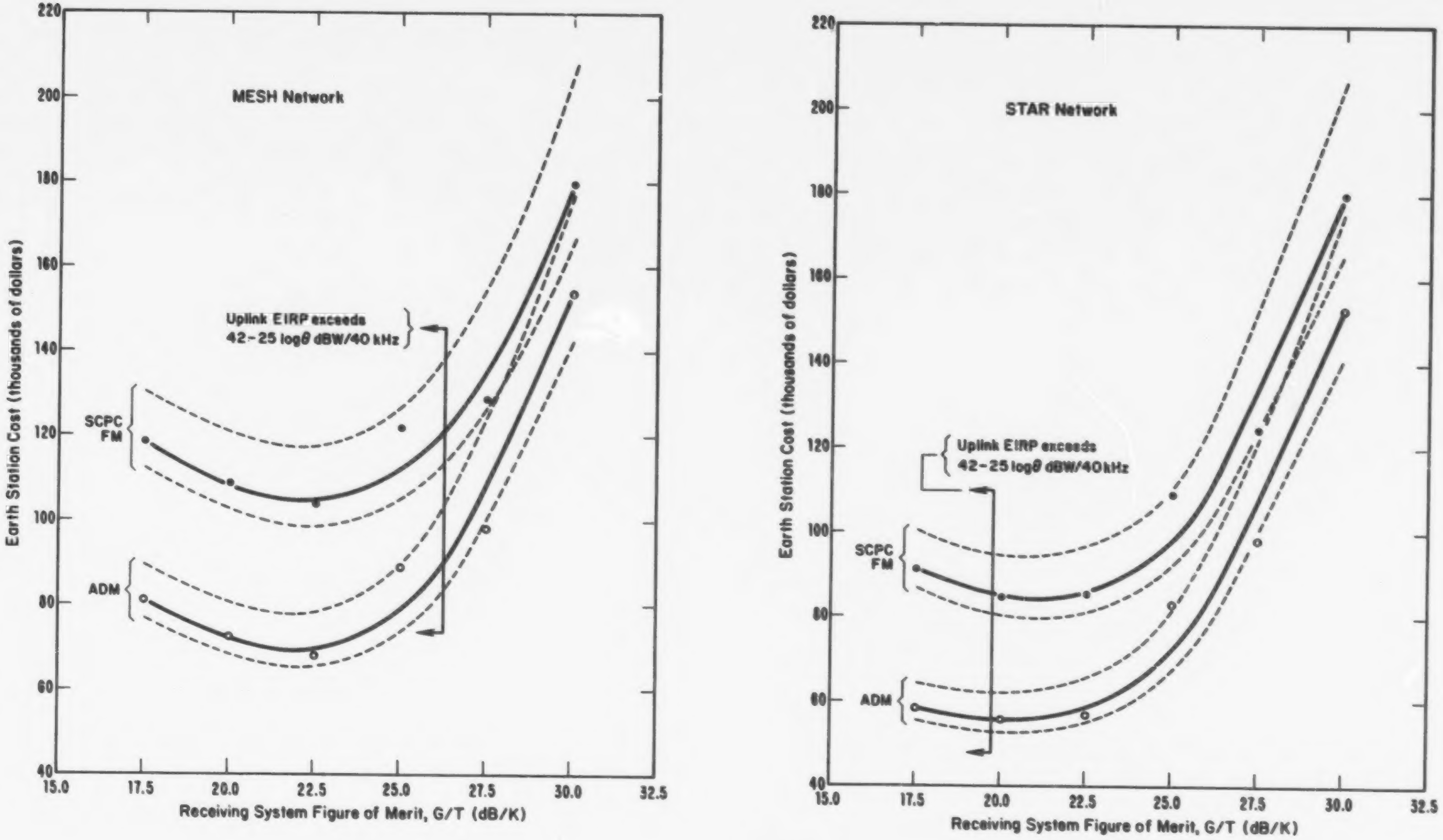
We notice that the earth-station costs developed from the component costs do not fall on smooth curves of cost versus receiving system figure of merit. We believe that is to be expected, though smooth curves have been drawn. However, most of the computed earth-station costs do lie within the cost uncertainty limits defined earlier and drawn on each figure.

Differences in earth station costs between SCPC-FM and ADM technologies arise in two ways. Adaptive delta modulation at a 16-kbps sampling rate can be multiplexed into a single bit stream at 48 kbps to which forward error



(a) (b)

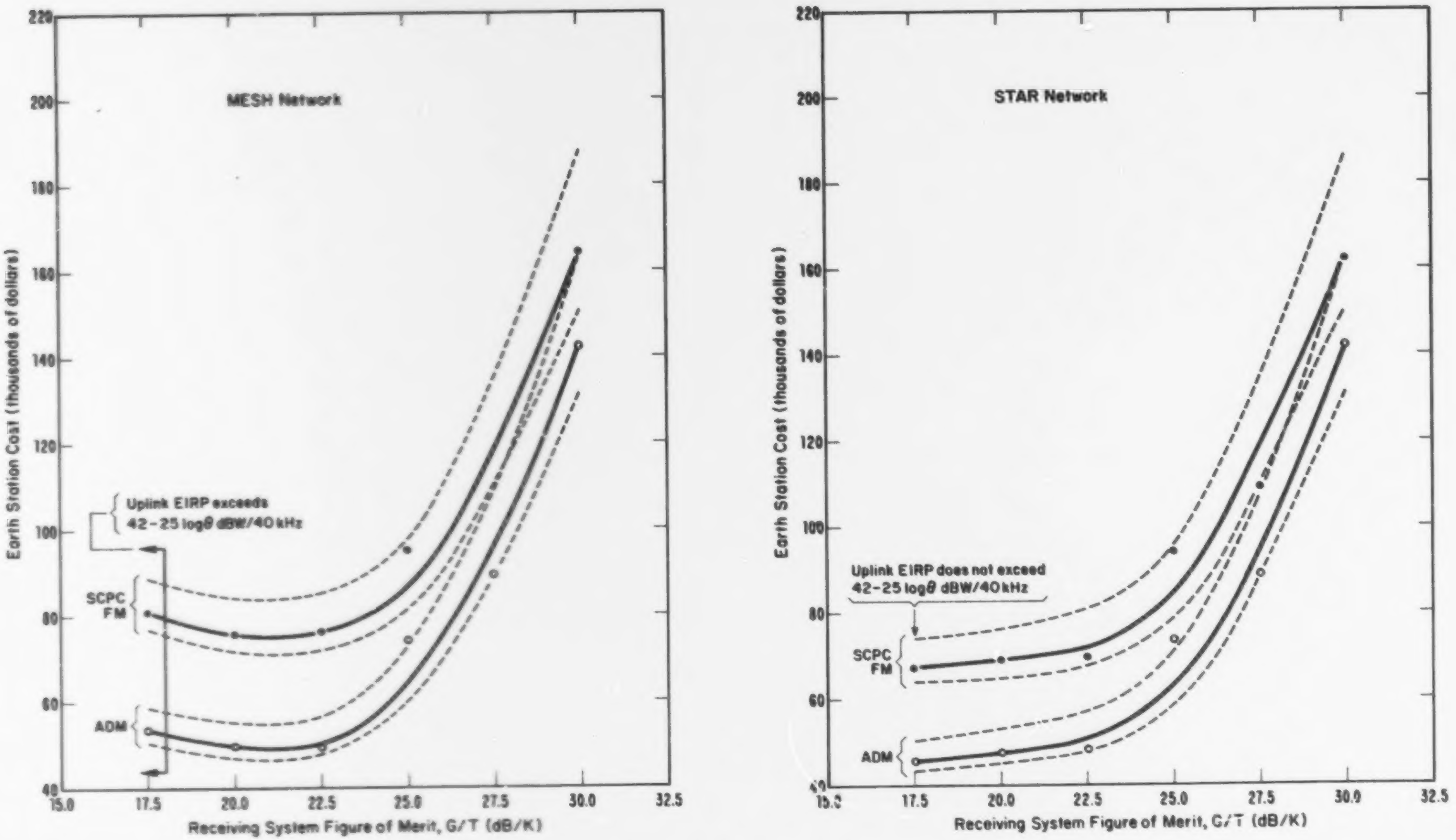
Figure 16. Estimates of earth station cost to provide three telephone circuits per earth station, C/N_0=54.0 dB-Hz, using single channel per carrier, frequency modulation (SCPC-FM) and adaptive delta modulation (ADM) and an INTELSAT global beam coverage satellite. Dashed lines indicate estimate uncertainties of +10% and -5% at G/T=17.5 dB/K increasing linearly to +15% and -7 1/2% at G/T=30.0 dB/K.



(a)

(b)

Figure 17. Estimates of earth station cost to provide three telephone circuits per earth station, C/N_0=54.0 dB-Hz, using single channel per carrier frequency modulation (SCPC-FM) and adaptive delta modulation (ADM) and an INTELSAT hemispheric beam coverage satellite. Dashed lines indicate estimate uncertainties of +10% and -5% at G/T=17.5 dB/ K increasing linearly to +15% and -7 1/2% at G/T=30.0 dB/ K.



(a)

(b)

Figure 18. Estimates of earth station cost to provide three telephone circuits per earth station, C/N_0=54.0 dB-Hz, using single channel per carrier frequency modulation (SCPC-FM) and adaptive delta modulation (ADM) and a Palapa satellite. Dashed lines indicate estimate uncertainties of +10% and -5% at G/T=17.5 dB/K increasing linearly to +15% and -7 1/2% at G/T=30.0 dB/K.

correction coding can be added. Assuming FEC at rate R=3/4 and using QPSK, the symbol rate is 32 k symbols/sec. Channel spacing, at 1.5 times the symbol rate, is 48 KHz. The required carrier-to-noise power density for this signal is 55 dB-Hz (which includes an operating margin of 2 dB), about equivalent to that required for companded frequency modulation. But, this technique provides three telephone channels on a single carrier rather than one channel per carrier as for SCPC-FM. Therefore, the required power from the high-power amplifier is less than for SCPC-FM, and there is no output-power back-off requirement for which allowance must be made. The second cost difference is in the Modem and voice modulation units. Our market survey shows that SCPC-FM common equipment (excluding frequency converters) and channel units for three channels will cost about $45,000, whereas the PSK Modem, FEC CODEC, MUX, and Voice CODECS for three channels of digitally encoded voice service will cost about $25,000.

5. SUMMARY OF ANALYSIS RESULTS

Figures 16 and 17 are based upon the INTELSAT global and hemispheric beams with the technical characteristics noted in Table 3 and Appendix B. If these technical characteristics are changed, then Figures 16 and 17 will change.

Figures 16, 17, and 18 give results for an example of telephone service with three circuits per earth station. The number of earth stations in any network would be limited by the satellite downlink EIRP and, secondarily in some cases, the bandwidth available in a quarter transponder. This example is a general example, however, because it has not been focused to specific thin-route applications.

From Figure 16, we observe that telephone service of three circuits per earth station in a MESH network using an INTELSAT global beam coverage satellite is technically possible for a receiving system figure of merit, G/T, of 22.5 dB/K at costs in the range of $70,000 to $85,000. This appears to be the minimum in the present state of the art and would use adaptive delta modulation digital technology. This example would be realized with an antenna diameter of 4.5 m, an LNA with 95K noise temperature, and an HPA with an output power level of 130 W. Another configuration for an earth station with G/T=22.5 dB/K would use an antenna of 6.0 m diameter, an LNA of 200K noise temperature, and an HPA of about 75 W.

In general, the only major limitation is the INTELSAT uplink EIRP restriction. To satisfy this requirement, the earth station G/T for the MESH network must be increased to 27.5 dB/K, as shown in Figure 16. The earth station cost increases above $100,000 as a result. For example, a G/T of 27.5 dB/K would require an antenna with 8.0 m diameter, an LNA with a noise temperature of 95K, and an HPA with an output power level of 13 W.

The information shown by Figure 16 indicates that service in a STAR network (with an INTELSAT global beam coverage satellite) could be provided with the remote earth station G/T = 25 dB/K (antenna diameter is 6 m). Minimum earth-station cost is estimated at about $75,000 for digital voice service up to about $105,000 for SCPC-FM service. Lower G/T earth stations could be used, but the INTELSAT uplink EIRP restriction would not be satisfied.

An INTELSAT satellite with hemispheric beam coverage has 2.5 dB more power available (than from an INTELSAT global beam coverage satellite) from a quarter transponder. This increased power will allow MESH network service using earth stations with antennas between 6 and 8 m in diameter (G/T=26 dB/K). The earth-station minimum costs are estimated to be about $90,000 using digital technology and $120,000 using SCPC-FM technology. Earth stations in a STAR network should cost about $55,000 or $60,000 using digital technology or $85,000 using SCPC-FM technology. In Figure 17 we notice these costs are close to absolute minimum estimated costs. These earth stations would use 4.5-m (or 5.0-m) antennas and have G/T=20 dB/K. Again, these results are the minimums that satisfy the uplink EIRP restriction.

The considerably higher power available from a domestic satellite such as PALAPA will allow use of still less expensive earth stations. The uplink EIRP restriction does not create a serious impact even for MESH networks. Estimated earth station costs range from about $45,000 or $50,000 to about $70,000 to $80,000 depending on the networking scheme and voice modulation technology chosen.

In summary, the analyses of service in this example of three telephone circuits per earth station and estimated earth station costs show that the minimum antenna size that could be used in an INTELSAT system is about 6 m for this level of service. An earth station with that antenna could operate only in a STAR network if the space segment is global beam coverage. A MESH network service would be marginal, but possible, perhaps, with limitations using hemispheric beam coverage. Earth-station cost is estimated to range from $70,000 to $120,000 depending on the voice modulation technology chosen and the space resources available to support the service.

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APPENDIX A: TELEPHONE SERVICE REQUIRED C/N_0 CALCULATIONS

Required carrier-to-noise power density (C/N_0) at the receiving earth station is the communications link parameter which establishes the selections of other controllable parameters in the link budget. These selectable parameters include the uplink EIRP, which is controlled by the transmitting antenna gain and the output power of the high-power amplifier, and the receiving system figure of merit (antenna-gain-to-receiving-system noise temperature, G/T). The type of service that is to be provided determines the required carrier-to-noise power density that must be realized. This appendix references the work of other researchers and includes some analysis to show the carrier-to-noise power densities that are required for the types of telephone service that are considered most likely to be implemented in development of thin-route communications systems, particularly systems for which assistance is provided by the Agency for International Development.

Companded frequency modulation as a single channel per carrier service, commonly referred to as SCPC-FM, requires a carrier-to-noise power density ratio of 53.0 dB-Hz if a phase-locked loop demodulator is used or 53.8 dB-Hz if an FM discriminator is used, according to Campanella, et al. (1977). As an approximate value, we assume SCPC-FM requires C/N_0 = 54.0 dB-Hz, which is one of the values used to compute the number of telephone channels that can be provided by 1/4 transponder, parametric in receiving system figure of merit (G/T). Other values of carrier-to-noise power density ratios which have been used are 48.0, 51.0 and 57.0 dB-Hz (3-dB intervals).

We show computations of required carrier-to-noise-power-density ratios for digital telephone service using various combinations of technology. Detailed computations are shown for three typical service configurations. These computations are followed by results in Table A-1 for several possible service combinations. Abbreviations in the notation used in that table have the following meanings. Single (or one) channel per carrier is denoted as SCPC, 2CPC denotes two channels per carrier, 4CPC denotes four channels per carrier, etc. Multiple channels per carrier may be realized by multiplexing individual channel bit streams to form a composite bit stream for rf modulation and transmission. ADM is used to denote adaptive delta modulation in a general sense, which includes continuously variable-slope delta modulation (CVSD) as well as other specific forms of delta modulation. Two-phase, or binary, phase shift keying (PSK) modulation is denoted by BPSK, and QPSK denotes four-phase, or quaternary, PSK. LPC denotes linear pre-

Table A-1. Required Carrier-to-Noise Power Density, C/N_0, Values for Various Choices of Voice Encoding, Forward Error Correction (FEC) Coding, and Modulation Techniques; BER = 10^{-4}

Voice Encoding and RF Modulation Technique	Required C/N_0 (dB-Hz)			20 dB Bandwidth (KHz) (99% Avg. Spectral Energy)			Minimum Channel Spacing (KHz) 1.5 (Bit Rate)			Ref.
	No FEC	R=3/4 FEC	R=1/2 FEC	No FEC	R=3/4 FEC	R=1/2 FEC	No FEC	R=3/4 FEC	R=1/2 FEC	
	(BPSK and QPSK)			(QPSK only)			(QPSK only)			
SCPC ADM at 9.6 kbps	52.2	48.0	46.3	26.9	35.8	53.8	7.2	9.6	14.4	1-5
16.0 kbps	54.4	50.2	48.5	44.8	59.7	89.6	12.0	16.0	24.0	1-5
32.0 kbps	57.4	53.2	51.5	89.6	119.5	179.2	24.0	32.0	48.0	1-5
2CPC ADM at 9.6 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	1-5
16.0 kbps	57.4	53.2	51.5	89.6	119.5	179.2	24.0	32.0	48.0	1-5
32.0 kbps	60.5	56.3	54.6	179.2	238.9	358.4	48.0	64.0	96.0	1-5
3CPC ADM at 9.6 kbps	57.0	52.8	51.1	80.6	107.5	161.3	21.6	28.8	43.2	1-5
16.0 kbps	59.2	55.0	53.3	134.4	179.2	268.8	36.0	48.0	72.0	1-5
32.0 kbps	62.2	58.0	56.3	268.8	358.4	537.6	72.0	96.0	144.0	1-5
4CPC ADM at 9.6 kbps	58.2	54.0	52.3	107.5	143.4	215.0	28.8	38.4	57.6	1-5
16.0 kbps	60.5	56.3	54.6	179.2	238.9	358.4	48.0	64.0	96.0	1-5
32.0 kbps	63.5	59.3	57.6	358.4	472.9	716.8	96.0	128.0	192.0	1-5
2CPC LPC at 4.8 kbps	52.2	48.0	46.3	26.9	35.8	53.8	7.2	9.6	14.4	1-5
9.6 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	1-5
4CPC LPC at 4.8 kbps	55.2	51.0	49.3	53.8	71.7	107.5	14.4	19.2	28.8	1-5
9.6 kbps	58.2	54.0	52.3	107.5	143.4	215.0	28.8	38.4	57.6	1-5

*DCDM denotes Digitally Controlled-Slope Delta Modulation.

Reference 1: Gray (1981).
Reference 2: Jacobs (1974).
Reference 3: Nesenbergs (1975).
Reference 4: Oetting (1979).
Reference 5: Spilker (1977).

dictive coding, a voice synthesis technology.

The bit energy-to-noise power density (E_b/N_o) required as a function of bit-error rate (BER) using phase shift keying modulation (BPSK and QPSK) is discussed by many authors. Typical values and many references are given by Oetting (1979). For thin-route satellite communication networks, available satellite EIRP rather than bandwidth generally limits the network size (i.e., the number of circuits that can be supported simultaneously). It often is desirable to use forward error correction (FEC) coding under these circumstances to reduce bit errors while utilizing a low carrier-to-noise-power-density ratio. Convolutional encoding with maximum likelihood (Viterbi) decoding is a good choice for optimizing the tradeoff between maximum coding gain and minimum implementation cost. The advantages of FEC coding to reduce bit errors also have been reported by many authors. Representative results for rate R=1/2 and rate R=3/4 coding are reported by Jacobs (1974) and Nesenbergs (1975).

Transmission with no FEC coding requires energy per bit-to-noise power density, E_b/N_o, of 10.4 dB for BER=10^{-4}. When rate R=3/4 coding, constraint length k=9 and eight level soft decision decoding is used, the required E_b/N_o is 6.2 dB for BER=10^{-4}. For rate R=1/2 coding, constraint length k=7 and eight level soft decision decoding, the required E_b/N_o is 4.5 dB for BER=10^{-4}. All values include about 2 dB for modem implementation losses. The required carrier-to-noise power density, C/N_o, is given by

$$\frac{C}{N_o}(\mathrm{dB}) = \frac{E_b}{N_o}(\mathrm{dB}) + 10\log_{10}\left(\frac{1}{T_b}\right) = \frac{E_b}{N_o}(\mathrm{dB}) + 10\log_{10} R_b$$

where T_b is the time per bit and R_b is the bit rate. Three calculations of typical required carrier-to-noise-power-density ratios follow.

First, we consider SCPC ADM at 32 kbps analog signal encoding rate with no error correction coding and with rates R=3/4 and R=1/2 FEC coding. These values apply to BPSK as well as QPSK rf modulation.

	No FEC	R=3/4FEC	R=1/2 FEC
Required E_b/N_o (dB)	10.4	6.2	4.5
Bit Rate Factor (dB-Hz)	45.0	45.0	45.0
Operating Margin (dB)	2.0	2.0	2.0
Required C/N_o (dB-Hz)	57.4	53.2	51.5

As a second example, we consider 4CPC at 16 kbps encoding rate, which provides an aggregate information bit rate of 64 kbps. Again, considering no FEC and rates R=3/4 and R=1/2 FEC coding, the required carrier-to-noise-power-density values are shown.

	No FEC	R=3/4 FEC	R=1/2 FEC
Required E_b/N_o (dB)	10.4	6.2	4.5
Bit Rate Factor (dB-Hz)	48.1	48.1	48.1
Operating Margin (dB)	2.0	2.0	2.0
Required C/N_o (dB-Hz)	60.5	56.3	54.6

For the third example, we consider 2CPC LPC at a channel sampling rate of 4.8 kbps, which provides an aggregate information rate of 9.6 kbps. The required carrier-to-noise-power-density values for no FEC and rates R=3/4 and R=1/2 FEC are shown.

	No FEC	R=3/4 FEC	R=1/2 FEC
Required E_b/N_o (dB)	10.4	6.2	4.5
Bit Rate Factor (dB-Hz)	39.8	39.8	39.8
Operating Margin (dB)	2.0	2.0	2.0
Required C/N_o (dB-Hz)	52.2	48.0	46.3

Following the calculation methodology demonstrated by these examples, the values shown in Table A-1 have been calculated.

We notice in Table A-1 that there are nine combinations of voice encoding and rf modulation techniques which will provide voice service at C/N_o=54.0 ± 1.0 dB-Hz. There are an additional 20 combinations which will provide service at C/N_o < 53.0 dB-Hz.

Voice service using digital techniques such as linear predictive coding at a 4.8 kbps sampling rate or adaptive delta modulation at a 16 kbps encoding rate will not be toll quality service. But, we believe a satisfactory grade of service for many applications, within the Rural Satellite Program and other similar types of program applications, can be provided using such digital techniques.

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APPENDIX B: SATELLITE TRANSPONDER TECHNICAL CHARACTERISTICS

Thin-route applications in general and Rural Satellite Program applications in particular undoubtedly will use leased transponder resources to provide the desired communication services. Throughout the world the most likely resources available for lease are those provided by INTELSAT. On a considerably more limited basis desired communication services may be provided using leased domestic satellite transponder resources, for example, in Indonesia and North America. Technical characteristics for satellite resources, which operate in the 3.700- to 4.200-GHz downlink and 5.925- to 6.425-GHz uplink bands, expected to be available for lease are shown in Table B-1 for INTELSAT IV, Table B-2 for INTELSAT IV-A, Table B-3 for INTELSAT V, Table B-4 for Palapa A, and Table B-5 for Palapa B.

Table B-1. Transponder Nominal Technical Characteristics for an INTELSAT IV Satellite*

Beam Coverage of Satellite Antenna	Global	
Satellite G/T (dB/K)	-18.6	
Transponder Leased Resources Characteristics	Flux Density (Rcving)	EIRP (Xmting)
Saturation	-67.5 dBW/m^2	22.0 dBW
Back-off Required for Multiple Carriers	-10.5 dB	-4.5 dB
Full-Transponder (36 MHz), Multiple-Carrier Operation	-78.0 dBW/m^2	17.5 dBW
One-Half Transponder (18 MHz)	-81.0 dBW/m^2	14.5 dBW
One-Quarter Transponder (9 MHz)	-84.0 dBW/m^2	11.5 dBW
Number of Transponders per Satellite	12 maximum	
Transponder Bandwidth	36 MHz	

*References: Kelley (1978) and Satellite Systems Digest (1981).

Table B-2. Transponder Nominal Technical Characteristics for an INTELSAT IV-A Satellite*

Beam Coverage of Satellite Antennas	Global and Hemispheric
Satellite G/T (dB/K)	-18.6 (Global) -11.6 (Hemispheric)

Transponder Leased Resources Characteristics

Global Beam Coverage	Same as shown in Table B-1.	
Hemispheric Beam Coverage	Flux Density (Rcving)	EIRP (Xmting)
Saturation	-67.5 dBW/m^2	26.0 dBW
Back-off Required for Multiple Carriers	-11.0 dB	-6.0 dB
Full-Transponder (36 MHz), Multiple-Carrier Operation	-78.5 dBW/m^2	20.0 dBW
One-Half Transponder (18 MHz)	-81.5 dBW/m^2	17.0 dBW
One-Quarter Transponder (9 MHz)	-84.5 dBW/m^2	14.0 dBW

Number of Transponders per Satellite	20 maximum
Transponder Bandwidth	36 MHz

*References: Kelley (1978) and Satellite Systems Digest (1981).

Table B-3. Transponder Nominal Technical Characteristics for an INTELSAT V Satellite* (6/4 GHz Operation)

Beam Coverage of Satellite Antennas		Global, Hemispheric, and Zonal	
		(F1-F4‡)	(F5-F9‡)
Satellite G/T (dB/ K)	(Global)	-18.6	-16.0
	(Hemispheric)	-11.6	-9.0
	(Zonal)	-8.6	-6.0

Transponder Leased Resources Characteristics	Flux Density (Receiving)				EIRP (Transmitting)
	Low Gain		High Gain		
	(F1-F4†)	(F5-F9†)	(F1-F4†)	(F5-F9†)	(F1-F9†)
Global Beam Coverage					
36 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-67.5	-70.1	-75.0	-77.6	23.5
18 MHz of Transponder Bandwidth, Multiple Carrier Operation	-81.0**	-83.6**	-88.5**	-91.1**	16.0**
9 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-84.0	-86.6	-91.5	-94.1	13.0
Hemispheric Beam Coverage					
72 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-64.5	-67.1	-72.0	-74.6	29.0
36 MHz of Transponder Bandwidth, Multiple Carrier Operation	-77.5**	-80.1**	-85.0**	-87.6**	20.0**
18 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-80.5	-83.1	-88.0	-90.6	17.0
9 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-83.5	-86.1	-91.0	-93.6	14.0
Zonal Beam Coverage					
72 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-64.5	-67.1	-72.0	-74.6	29.0
36 MHz of Transponder Bandwidth, Multiple Carrier Operation	-77.5**	-80.1**	-85.0**	-87.6**	20.0**
18 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-80.5	-83.1	-88.0	-90.6	17.0
9 MHz of Transponder Bandwidth, Single or Multiple Carrier Operation	-83.5	-86.1	-91.0	-93.6	14.0

Number of Transponders per Satellite	15 maximum
Transponder Bandwidth (MHz)	36, 41, 72, and 77

* References: INTELSAT (1981) and Satellite Systems Digest (1981).

‡ Spacecraft numbers.

** 2 dB higher for single carrier operation.

Table B-4. Transponder Nominal Technical Characteristics for a Palapa A Satellite* (Typical for Domestic Systems Which Use Hughes HS 333D Satellites)

Beam Coverage of Satellite Antenna	Shaped for Indonesia	
Satellite G/T (dB/K)	-7.0	
Transponder Leased Resources Characteristics	Flux Density (Rcving)	EIRP (Xmting)
Saturation	-80.0 dBW/m^2	32.0 dBW
Back-off Required for Multiple Carriers	-7.0 dB	-4.0 dB
Full-Transponder, Multiple-Carrier Operation	-87.0 dBW/m^2	28.0 dBW
One-Half Transponder	-90.0 dBW/m^2	25.0 dBW
One-Quarter Transponder	-93.0 dBW/m^2	22.0 dBW
Number of Transponders per Satellite	12	
Transponder Bandwidth	36 MHz	

*References: Sanderson and Elbert (1976) and Satellite Systems Digest (1981).

Table B-5. Transponder Nominal Technical Characteristics for a Palapa B Satellite* (Typical for Domestic Satellite Systems Which Use Hughes 376 Satellites)

Beam Coverage of Satellite Antenna	Shaped for Indonesia, Philippines, and Thailand	
Satellite G/T (dB/K)	-5.0	
Transponder Leased Resources Characteristics	Flux Density (Rcving)	EIRP (Xmting)
Saturation	-80.0 dBW/m^2	34.0 dBW
Back-off Required for Multiple Carriers	-7.0 dB	-4.0 dB
Full-Transponder, Multiple-Carrier Operation	-87.0 dBW/m^2	30.0 dBW
One-Half Transponder	-90.0 dBW/m^2	27.0 dBW
One-Quarter Transponder	-93.0 dBW/m^2	24.0 dBW
Number of Transponders per Satellite	24	
Transponder Bandwidth	36 MHz	

*References: Hughes (1980) and Satellite Systems Digest (1981).

The nominal values given in these tables for satellite receiving system G/T and EIRP are for beam edge. For locations within the beam, a geographical advantage of up to 3 dB or more, depending on the satellite, will be realized for each parameter. This benefit occurs because of the antenna pattern (higher gain as earth station locations approach the antenna aim point) and reduced path loss.

REFERENCES

Hughes (1980), Palapa - B Fact Sheet, Hughes Aircraft Company, April.

INTELSAT (1981), INTELSAT V and V-A Leased Transponder Definitions, Document BG-47-7E, W/9/81 and BG/T-38-5E, W/8/81, Attachment No. 1.

Kelley, T. M. (1978), Domestic satellite communications using leased INTELSAT transponders, Conference Record of ICC '78, Vol. I, Toronto, Canada.

Sanderson, C. C.,and B. R. Elbert (1976), Communication system design of Indonesian domestic satellite system, WESCON Technical Papers, Paper 9/2, September.

Satellite Systems Engineering, Inc. (1981), Satellite Systems Digest, (7315 Wisconsin Avenue, Washington, D. C. 20014).

APPENDIX C: EARTH STATION TECHNICAL CHARACTERISTICS

A number of manufacturers were contacted regarding the earth stations and/or earth station components which they market. These contacts were made to determine characteristics and costs. Much of the information obtained by these contacts is reported in Section 4 of the report, and that information will not be repeated in this Appendix. Only supplementary information is provided in this Appendix.

We have assumed earth-station receiving-system figure of merit (G/T) values of 17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K in the parametric analysis approach taken by this report. Figure 4 of the report is a plot of receiving system figure of merit versus LNA noise temperature, parametric in antenna aperture diameter. In developing the data for that figure, we used information obtained from manufacturers regarding main-beam antenna gain versus aperture diameter to calculate antenna efficiency. Based on those calculations, typical receiving and transmitting operation efficiencies have been assumed and used to calculate typical gain as a function of frequency. The assumed efficiencies are 65% at 3.950 GHz (mid-band for the receiving band) and 55% at 6.175 GHz (mid-band for the transmitting band). Antenna gain was calculated using the expression

$$G(\mathrm{dB}) = 10 \log_{10} \left(\varepsilon \frac{4\pi A}{\lambda^2}\right),$$

where: A = area, in square meters, of the antenna aperture,

ε = antenna efficiency as a function of frequency, and

λ = wavelength, in meters, of the received or transmitted energy.

Calculated gains as a function of frequency and antenna aperture diameter are shown in Table C-1.

Table C-1. Calculated Antenna Gains at 3.950 GHz and 6.175 GHz, Assuming Efficiency is 65% for Receiving and 55% for Transmitting Applications.

Antenna Aperture, m	Gain at 3.950 GHz, dB	Gain at 6.175 GHz, dB
3.0	40.0	43.2
4.5	43.5	46.7
6.0	46.0	49.2
8.0	48.5	51.7
10.0	50.5	53.6

The receiving system noise temperature must be known or assumed to calculate the receiving system figure of merit, G/T. System noise temperature, in that ratio, is designated more precisely as T_S, where

$$T_S = \frac{T_A}{\ell} + T_\ell + T_E \ (^\circ K).$$

In the expression above,

T_A = antenna, noise temperature,

ℓ = resistive losses (numeric) between the antenna and the receiver (usually the LNA which is the first component of the receiver),

T_ℓ = contribution to system noise temperature due to resistive losses, ℓ, $=(1 - \frac{1}{\ell})290K$, and

T_E = equivalent noise temperature of the receiver, which includes the LNA.

In a system of two cascaded amplifiers, the effective noise temperature is the sum of the noise temperature of the first amplifier plus the noise temperature of the second amplifier divided by the gain of the first amplifier, i.e., $T_1 + \frac{T_2}{g_1}$. The low-noise amplifier normally is the first component of the earth station receiver. In our survey of manufacturers, we found that gain for GaAs FET low-noise amplifiers (reported in Section 4.2) typically is 50 dB or about 10^5 numeric. We, therefore, assume that $T_E = T_{LNA}$, where T_{LNA} = noise temperature of the low-noise amplifier. Secondly, we assume that $T_A = 25K$ or less and that $\ell = 0.2$ dB. We believe these values are representative of maximum values that would be found in a well-engineered earth station for thin-route applications. Using the values assumed, we calculate $T_A/\ell + T_\ell = 35K$ with which we simplify the system noise temperature expression to

$$T_S = T_{LNA} + 35 \ (K).$$

The gains from Table C-1 and T_S using the above expression are used to calculate G/T as

$$\frac{G}{T} = 10 \log_{10}\left(\frac{\text{antenna gain (numeric)}}{T_S}\right).$$

Table C-2 is a matrix of G/T values for antenna gain (or antenna aperture diameter) versus system noise temperature.

Table C-2. Receiving System Figure of Merit, G/T, as a Function of Antenna Gain (Aperture) and System Noise Temperature, T_S

Antenna Diameter, m	Receiving Antenna Gain, dB	T_s, K (T_{LNA})				
		90 (55)	125 (90)	155 (120)	185 (150)	235 (200)
3.0	40.0	20.5	19.0	18.1	17.3	16.3
4.5	43.5	24.0	22.6	21.6	20.9	19.8
6.0	46.0	26.5	25.1	24.1	23.4	22.3
8.0	48.5	29.0	27.6	26.6	25.9	24.8
10.0	50.5	30.9	29.5	28.6	27.8	26.8

We notice that within each column there is a 10.5-dB spread due to antenna size, and within each row there is a spread of about 4 dB due to the low-noise-amplifier noise temperature.

Supposing that the remote earth-station antenna size is determined by the figure of merit (G/T) that must be used to obtain the required carrier-to-noise power density (C/N_0) to provide the selected type of service, then the only way in which the uplink EIRP for the return link can be obtained is by adjustment of the output power from the high-power amplifier. Table C-1 shows transmitting antenna gain as a function of antenna size. Output power from the HPA on a per-carrier basis is determined from the simple expression

HPA Output Power (dBW) = Uplink EIRP (dBW) - Antenna Gain (dB).

The link budgets in Appendix D show the HPA output power on a per-carrier basis to range from <0.1 W (Palapa A) to almost 2 kW (INTELSAT Global) MESH network of stations. In a STAR network, the HPA output power requirements on a per-carrier basis range from <0.1 W (Palapa A) to 72.4 W (INTELSAT Global) for the remote station and from <0.1 W (Palapa A) to 128.8 W (INTELSAT Global) for the central station. In single-channel-per-carrier applications the total output-power requirement would be increased by a factor equal to the number of channels to be provided plus a required back-off of ∿4 dB for multicarrier operation. As a general rule, if the total output-power requirement exceeds about 10 dBW/40 kHz, the INTELSAT off-axis EIRP restriction of $42 - 25 \log \theta$ dBW/40 KHz will be exceeded.

APPENDIX D: LINK BUDGET CALCULATIONS

In our parametric analysis approach, we have assumed six remote-earth-station figure-of-merit (G/T) values ranging from 17.5 to 30.0 dB/K; four carrier-to-noise power density (C/N_o) values ranging from 48.0 to 57.0 dB-Hz; three possible types of satellite transponder resources, namely 1/4 transponder on an INTELSAT with global-beam coverage satellite, INTELSAT with hemispheric-beam coverage satellite, or a Palapa A satellite; and MESH and STAR network configurations. Link budgets for each combination of these parameters are given in this appendix. A brief discussion of each parameter in the link budget is given first.

Item 1 shows the antenna diameter and/or earth-station figure of merit (G/T) for the remote earth station in a STAR network or the common station in a MESH network.

Item 2 is the power that must be delivered by the high-power amplifier to the antenna. This power is the difference between the uplink EIRP (item 4) and the calculated antenna gain, midband, for uplink frequencies (item 3).

Item 3 is the calculated antenna gain, midband for uplink frequencies. Appendix C provides details of the calculated gains. The gain is for the common earth station in a MESH network. Item 3 in the remote-station-to-central-station link budgets for a STAR network is the gain of the remote station antenna. In the central station-to-remote station link budget, item 3 is calculated gain for the central earth station which is assumed to be an INTELSAT Standard B or equivalent capability earth station.

Item 4 is the uplink EIRP, denoted later as $EIRP_{up}$, that will provide the required total carrier-to-noise power density $(C/N_o)_{tot}$, item 23.

Item 5 is an assumed value for uplink losses, denoted later as $L_{misc-up}$, from a variety of causes such as pointing error, polarization loss, atmospheric absorption, etc.

Item 6 is the calculated (free-space) uplink propagation loss, denoted later as L_{fs-up}, for an assumed elevation angle of 20°.

Item 7 is the power flux density at the satellite resulting from the uplink EIRP shown as item 4. Power flux density (PFD) is calculated using the following expression:

$$\text{PFD (dBW/m}^2) = EIRP_{up} - L_{misc-up}\text{ (dB)} - L_{fs-up}\text{ (dB)} + 10 \log_{10} \frac{4\pi}{\lambda^2} .$$

Item 8 shows the maximum power flux density allowed for multicarrier operation. Refer to Appendix B for values that are appropriate for each type of satellite transponder resource. Item 7 value must not exceed Item 8 value.

Item 9 shows Boltzmann's constant, denoted as K, which is used in calculating the uplink and downlink carrier-to-noise power density ratios, items 11 and 20, respectively.

Item 10 shows the satellite figure of merit, denoted later as $(G/T)_{sat}$. Refer to Appendix B for values that are appropriate for each type of satellite resource. The quantity is used in calculating the uplink carrier-to-noise power density ratio.

Item 11 is the calculated uplink carrier-to-noise power density, $(C/N_o)_{up}$, which is calculated using the following expression:

$$\left(\frac{C}{N_o}\right)_{up} \text{ (dB-Hz)} = \text{PFD (dBW/m}^2\text{)} + \left(\frac{G}{T}\right)_{sat} - 10 \log_{10} \frac{4\pi}{\lambda^2} - \text{K (dBW/K-Hz)} .$$

Item 12 shows the calculated total satellite system gain, that is, the gain of the receiving antenna plus gain in the transponder electronics plus gain of the transmitting antenna. This gain is determined by calculating the gain that is required to produce the maximum downlink EIRP (shown in Appendix 2) when the uplink signal just meets the maximum, multicarrier power flux density shown as item 8 (also given in Appendix B). These calculations are shown below for the three types of satellite resources considered in this report.

	INTELSAT Global	INTELSAT Hemispheric	Palapa A
Max. Available Downlink EIRP (dBW):	11.5	14.0	22.0
Max. Multicarrier Flux Density (dBW/m^2):	-84.0	-84.5	-93.0
Gain of 1 m^2 Antenna, 100% Efficient (dB):	-37.3	-37.3	-37.3
Required Gain to Obtain Max. EIRP (dB):	132.8	135.8	152.3

Item 13 is the downlink EIRP (per carrier), EIRP_{dn}, that will provide the total required carrier-to-noise power density shown as item 23. This necessary downlink EIRP is calculated using the following expression:

$$\text{EIRP}_{dn}\text{(dBW)} = \left(\frac{C}{N_o}\right)_{dn} \text{(dB-Hz)} - \left(\frac{G}{T}\right)_{es} + L_{misc\text{-}dn}\text{(dB)} + L_{fs\text{-}dn}\text{(dB)} + \text{K(dBW/K-Hz)} .$$

$\left(\frac{G}{T}\right)_{es}$ denotes figure of merit for the earth station.

Item 14 is the maximum level of interference caused by adjacent transponder intermodulation that is allowed. INTELSAT specifies that this interference must not exceed -40.0 dBW/4 kHz, or -76.0 dBW/Hz.

Item 15 is an assumed value for downlink losses, denoted as $L_{misc-dn}$, from a variety of causes such as pointing error, polarization loss, atmospheric absorption, etc.

Item 16 is the calculated (free space) downlink propagation loss, denoted as L_{fs-dn}, for an assumed elevation angle of 20°.

Item 17 is the calculated antenna gain, midband, for downlink frequencies. Appendix C provides details of calculating the gain. The gain is for the common earth stations in a MESH network. Item 17 is (receive) gain of the central, standard B earth station antenna in the STAR network in a remote station-to-central station link budget. For the STAR network, central station-to-remote station link budget, item 17 is gain of the remote earth station, receive mode.

Item 18 is the receiving system noise temperature. System noise temperature and calculation methods are discussed in Appendix C.

Item 19 is the earth-station figure of merit calculated from items 17 and 18 according to the method discussed in Appendix C or a value from some other source such as 31.7 dB/K for an INTELSAT Standard B earth station.

Item 20 is the downlink carrier-to-noise power density, $(\frac{C}{N_o})_{dn}$, which is calculated using the following expression:

$$(\frac{C}{N_o})_{dn}\,(\text{dB-Hz}) = EIRP_{dn}(\text{dBW}) + (\frac{G}{T})_{es}(\text{dB/K}) - L_{misc-dn}(\text{dB}) - L_{fs-dn}(\text{dB}) - K(\text{dBW/K-Hz}).$$

Item 21 is the downlink carrier-to-intermodulation noise power density, denoted as $(\frac{C}{I})_{dn}$, which is calculated using the following expression:

$$(\frac{C}{I})_{dn}(\text{dB-Hz}) = EIRP_{dn}(\text{dBW}) - L_{misc-dn}(\text{dB}) - I(\text{dBW/Hz}).$$

Item 22 is the total, system carrier-to-noise power density, denoted as $(C/N_o)_{tot}$ which is calculated using the following expression:

$$(\frac{C}{N_o})^{-1}_{tot}\,(\text{numeric}) = (\frac{C}{N_o})^{-1}_{up}(\text{numeric}) + (\frac{C}{N_o})^{-1}_{dn}(\text{numeric}) + (\frac{C}{I})^{-1}_{dn}(\text{numeric})$$

and, of course,

$$(\frac{C}{N_o})_{tot}\,(\text{dB-Hz}) = 10\log_{10}(\frac{C}{N_o})_{tot}\,(\text{numeric}).$$

Item 23 is the carrier-to-noise power density that must be provided by the system according to the type of service the system is intended to provide.

Tables D-1 through D-36 show link budgets for the two network options, three satellite resource options, and four carrier-to-noise power density ratio options considered in this report.

Table D-1. Link Budget for Required C/N_o = 48.0 dB-Hz for a MESH Network using an INTELSAT Global Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	23.4	20.9	17.4	15.0	12.5	10.0	7.5	5.1	0.8
		W	218.8	123.0	55.0	31.6	17.8	10.0	5.6	3.2	1.2
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	66.6	64.1		61.7		59.2		56.8	54.4
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-96.8	-99.3		-101.7		-104.2		-106.6	-109.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0		-84.0		-84.0		-84.0	-84.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6		-18.6		-18.6		-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	75.9	73.4		71.0		68.5		66.1	63.7
12.	Satellite System Gain	dB	132.8	132.8		132.8		132.8		132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	-1.3	-3.8		-6.2		-8.7		-11.1	-13.5
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	48.0	48.0		48.1		48.1		48.2	48.3
21.	Downlink Rec'd. C/I	dB-Hz	74.2	71.7		69.3		66.8		64.4	62.0
22.	System C/N_o (Total)	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0
23.	Required C/N_o	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0

Table D-2. Link Budget for Required C/N_0 = 48.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	9.6	6.1	3.6	1.1	-0.8
		W	9.1	4.1	2.3	1.3	0.8
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			52.8		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-110.6		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-18.6		
11.	Uplink Rec'd. C/N_0	dB-Hz			62.1		
12.	Satellite System Gain	dB			132.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-15.1		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_0	dB-Hz			48.4		
21.	Downlink Rec'd. C/I	dB-Hz			60.4		
22.	System C/N_0 (Total)	dB-Hz			48.0		
23.	Required C/N_0	dB-Hz			48.0		

Table D-3. Link Budget for Required C/N_o = 48.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	12.1	9.6	7.2	4.7	2.3	-0.1
		W	16.2	9.1	5.2	3.0	1.7	1.0
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	66.6	64.1	61.7	59.2	56.8	54.4
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-96.8	-99.3	-101.7	-104.2	-106.6	-109.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0	-84.0	-84.0	-84.0	-84.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6	-18.6	-18.6	-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	75.9	73.4	71.0	68.5	66.1	63.7
12.	Satellite System Gain	dB	132.8	132.8	132.8	132.8	132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	-1.3	-3.8	-6.2	-8.7	-11.1	-13.5
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	------------------------- See Figure 4 -------------------------					
18.	RCV Sys. Noise Temp.	dB/K	------------------------- See Figure 4 -------------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	48.0	48.0	48.1	48.1	48.2	48.3
21.	Downlink Rec'd. C/I	dB-Hz	74.2	71.7	69.3	66.8	64.4	62.0
22.	System C/N_o (Total)	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0
23.	Required C/N_o	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0

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Table D-4. Link Budget for Required C/N_o = 51.0 dB-Hz for a MESH Network using an INTELSAT Global Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	26.4	23.9	20.4	18.0	15.5	13.0	10.5	8.1	3.8
		W	436.5	245.5	109.6	63.1	35.5	20.0	11.2	6.5	2.4
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	69.6	67.1		64.7		62.2		59.8	57.4
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-93.8	-96.3		-98.7		-101.2		-103.6	-106.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0		-84.0		-84.0		-84.0	-84.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6		-18.6		-18.6		-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	78.9	76.4		74.0		71.5		69.1	66.7
12.	Satellite System Gain	dB	132.8	132.8		132.8		132.8		132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.7	-0.8		-3.2		-5.7		-8.1	-10.5
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	51.0	51.0		51.1		51.1		51.2	51.3
21.	Downlink Rec'd. C/I	dB-Hz	77.2	74.7		72.3		69.8		67.4	65.0
22.	System C/N_o (Total)	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0
23.	Required C/N_o	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0

Table D-5. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	12.6	9.1	6.6	4.1	2.2
		W	18.2	8.1	4.6	2.6	1.7
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			55.8		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-107.6		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-18.6		
11.	Uplink Rec'd. C/N_o	dB-Hz			65.1		
12.	Satellite System Gain	dB			132.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-12.1		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			51.4		
21.	Downlink Rec'd. C/I	dB-Hz			63.4		
22.	System C/N_o (Total)	dB-Hz			51.0		
23.	Required C/N_o	dB-Hz			51.0		

Table D-6. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	15.1	12.6	10.2	7.7	5.3	2.9
		W	32.4	18.2	10.5	5.9	3.4	1.9
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	69.6	67.1	64.7	62.2	59.8	57.4
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-93.8	-96.3	-98.7	-101.2	-103.6	-106.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0	-84.0	-84.0	-84.0	-84.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6	-18.6	-18.6	-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	78.9	76.4	74.0	71.5	69.1	66.7
12.	Satellite System Gain	dB	132.8	132.8	132.8	132.8	132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.7	-0.8	-3.2	-5.7	-8.1	-10.5
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	-------------------------------- See Figure 4 --------------------------------					
18.	RCV Sys. Noise Temp.	dB/K	-------------------------------- See Figure 4 --------------------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	51.0	51.0	51.1	51.1	51.2	51.3
21.	Downlink Rec'd. C/I	dB-Hz	77.2	74.7	72.3	69.8	67.4	65.0
22.	System C/N_o (Total)	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0
23.	Required C/N_o	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0

Table D-7. Link Budget for Required C/N_0 = 54.0 dB-Hz for a MESH Network Using an INTELSAT Global Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	29.4	27.3	23.4	21.0	18.5	16.0	13.5	11.1	6.8
		W	871.0	537.0	218.8	125.9	70.8	39.8	22.4	12.9	4.8
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	72.6	70.1		67.7		65.2		62.8	60.4
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3		-95.7		-98.2		-100.6	-103.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0		-84.0		-84.0		-84.0	-84.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6		-18.6		-18.6		-18.6	-18.6
11.	Uplink Rec'd. C/N_0	dB-Hz	81.9	79.4		77.0		74.5		72.1	69.7
12.	Satellite System Gain	dB	132.8	132.8		132.8		132.8		132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2		-0.2		-2.7		-5.1	-7.5
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	54.0	54.0		54.1		54.1		54.2	54.3
21.	Downlink Rec'd. C/I	dB-Hz	80.2	77.7		75.3		72.8		70.4	68.0
22.	System C/N_0 (Total)	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0
23.	Required C/N_0	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0

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Table D-8. Link Budget for Required C/N_o = 54.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	15.6	12.1	9.6	7.1	5.2
		W	36.3	16.2	9.1	5.1	3.3
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			58.8		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-104.6		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-18.6		
11.	Uplink Rec'd. C/N_o	dB-Hz			68.1		
12.	Satellite System Gain	dB			132.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-9.1		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			54.5		
21.	Downlink Rec'd. C/I	dB-Hz			66.4		
22.	System C/N_o (Total)	dB-Hz			54.0		
23.	Required C/N_o	dB-Hz			54.0		

Table D-9. Link Budget for Required C/N_0 = 54.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	18.1	15.6	13.2	10.7	8.3	5.9
		W	64.6	36.3	20.9	11.7	6.8	3.9
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	72.6	70.1	67.7	65.2	62.8	60.4
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3	-95.7	-98.2	-100.6	-103.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0	-84.0	-84.0	-84.0	-84.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6	-18.6	-18.6	-18.6	-18.6
11.	Uplink Rec'd. C/N_0	dB-Hz	81.9	79.4	77.0	74.5	72.1	69.7
12.	Satellite System Gain	dB	132.8	132.8	132.8	132.8	132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2	-0.2	-2.7	-5.1	-7.5
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	------------------------------- See Figure 4 -------------------------------					
18.	RCV Sys. Noise Temp.	dB/K	------------------------------- See Figure 4 -------------------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	54.0	54.0	54.1	54.1	54.2	54.3
21.	Downlink Rec'd. C/I	dB-Hz	80.2	77.7	75.3	72.8	70.4	68.0
22.	System C/N_0 (Total)	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0
23.	Required C/N_0	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0

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Table D-10. Link Budget for Required C/N_o = 57.0 dB-Hz for a MESH Network Using an INTELSAT Global Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	32.4	29.9	26.4	24.0	21.5	19.0	16.5	14.1	9.8
		W	1737.0	977.2	436.5	251.2	141.3	79.4	44.7	25.7	9.5
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	75.6	73.1		70.7		68.2		65.8	63.4
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-87.8	-90.3		-92.7		-95.2		-97.6	-100.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0		-84.0		-84.0		-84.0	-84.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6		-18.6		-18.6		-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	84.9	82.4		80.0		77.5		75.1	72.7
12.	Satellite System Gain	dB	132.8	132.8		132.8		132.8		132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.7	5.2		2.8		0.3		-2.1	-4.5
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------------------------- See Figure 4 ----------------------------								
18.	RCV Sys. Noise Temp.	dB/K	---------------------------- See Figure 4 ----------------------------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.0	57.0		57.1		57.1		57.2	57.3
21.	Downlink Rec'd. C/I	dB-Hz	83.2	80.7		78.3		75.8		73.4	71.0
22.	System C/N_o (Total)	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0

Table D-11. Link Budget for Required C/N_0 = 57.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	18.6	15.1	12.6	10.1	8.2
		W	72.4	32.4	18.2	10.2	6.6
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			61.8		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-101.6		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-18.6		
11.	Uplink Rec'd. C/N_0	dB-Hz			71.1		
12.	Satellite System Gain	dB			132.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-6.1		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_0	dB-Hz			57.5		
21.	Downlink Rec'd. C/I	dB-Hz			69.4		
22.	System C/N_0 (Total)	dB-Hz			57.0		
23.	Required C/N_0	dB-Hz			57.0		

Table D-12. Link Budget for Required C/N_o = 57.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Global Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	21.1	18.6	16.2	13.7	11.3	8.9
		W	128.8	72.4	41.7	23.4	13.5	7.8
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	75.6	73.1	70.7	68.2	65.8	63.4
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-87.8	-90.3	-92.7	-95.2	-97.6	-100.0
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.0	-84.0	-84.0	-84.0	-84.0	-84.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-18.6	-18.6	-18.6	-18.6	-18.6	-18.6
11.	Uplink Rec'd. C/N_o	dB-Hz	84.9	82.4	80.0	77.5	75.1	72.7
12.	Satellite System Gain	dB	132.8	132.8	132.8	132.8	132.8	132.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.7	5.2	2.8	0.3	-2.1	-4.5
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------					
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.0	57.0	57.1	57.1	57.2	57.3
21.	Downlink Rec'd. C/I	dB-Hz	83.2	80.7	78.3	75.8	73.4	71.0
22.	System C/N_o (Total)	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0

Table D-13. Link Budget for Required C/N_o = 48.0 dB-Hz for a MESH Network Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	20.4	17.9	14.4	11.9	9.4	7.0	4.5	2.0	-2.3
		W	109.6	61.7	27.5	15.5	8.7	5.0	2.8	1.6	0.6
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	63.6	61.1		58.6		56.2		53.7	51.3
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-99.8	-102.3		-104.8		-107.2		-109.7	-112.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5		-84.5		-84.5		-84.5	-84.5
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6		-11.6		-11.6		-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	79.9	77.4		74.9		72.5		70.0	67.6
12.	Satellite System Gain	dB	135.8	135.8		135.8		135.8		135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	-1.3	-3.8		-6.3		-8.7		-11.2	-13.6
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------------------------- See Figure 4 ----------------------------								
18.	RCV Sys. Noise Temp.	dB/K	---------------------------- See Figure 4 ----------------------------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	48.0	48.0		48.0		48.1		48.1	48.2
21.	Downlink Rec'd. C/I	dB-Hz	74.2	71.7		69.2		66.8		64.3	61.9
22.	System C/N_o (Total)	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0
23.	Required C/N_o	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0

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Table D-14. Link Budget for Required C/N_o = 48.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	6.5	3.0	0.5	-2.0	-3.9
		W	4.5	2.0	1.1	0.6	0.4
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			49.7		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-113.7		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.5		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-11.6		
11.	Uplink Rec'd. C/N_o	dB-Hz			66.0		
12.	Satellite System Gain	dB			135.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-15.2		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			48.3		
21.	Downlink Rec'd. C/I	dB-Hz			60.3		
22.	System C/N_o (Total)	dB-Hz			48.0		
23.	Required C/N_o	dB-Hz			48.0		

Table D-15. Link Budget for Required C/N_o = 48.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	9.1	6.6	4.1	1.7	-0.8	-3.2
		W	8.1	4.6	2.6	1.5	0.8	0.5
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	63.6	61.1	58.6	56.2	53.7	51.3
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-99.8	-102.3	-104.8	-107.2	-109.7	-112.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5	-84.5	-84.5	-84.5	-84.5
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6	-11.6	-11.6	-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	79.9	77.4	74.9	72.5	70.0	67.6
12.	Satellite System Gain	dB	135.8	135.8	135.8	135.8	135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	-1.3	-3.8	-6.3	-8.7	-11.2	-13.6
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	----------- See Figure 4 -----------					
18.	RCV Sys. Noise Temp.	dB/K	----------- See Figure 4 -----------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	48.0	48.0	48.0	48.1	48.1	48.2
21.	Downlink Rec'd. C/I	dB-Hz	74.2	71.7	69.2	66.8	64.3	61.9
22.	System C/N_o (Total)	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0
23.	Required C/N_o	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0

Table D-16. Link Budget for Required C/N_o = 51.0 dB-Hz for a MESH Network Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	23.4	20.9	17.4	14.9	12.4	10.0	7.5	5.0	0.7
		W	218.8	123.0	55.0	30.9	17.4	10.0	5.6	3.2	1.2
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	66.6	64.1		61.6		59.2		56.7	54.3
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-96.8	-99.3		-101.8		-104.2		-106.7	-109.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5		-84.5		-84.5		-84.5	-84.5
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6		-11.6		-11.6		-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	82.9	80.4		77.9		75.5		73.0	70.6
12.	Satellite System Gain	dB	135.8	135.8		135.8		135.8		135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.7	-0.8		-3.3		-5.7		-8.2	-10.6
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	51.0	51.0		51.0		51.1		51.1	51.2
21.	Downlink Rec'd. C/I	dB-Hz	77.2	74.7		72.2		69.8		67.3	64.9
22.	System C/N_o (Total)	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0
23.	Required C/N_o	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0

Table D-17. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	9.5	6.0	3.5	1.0	-0.9
		W	8.9	4.0	2.2	1.3	0.8
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			52.7		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-110.7		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.5		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-11.6		
11.	Uplink Rec'd. C/N_o	dB-Hz			69.0		
12.	Satellite System Gain	dB			135.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-12.2		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			51.3		
21.	Downlink Rec'd. C/I	dB-Hz			63.3		
22.	System C/N_o (Total)	dB-Hz			51.0		
23.	Required C/N_o	dB-Hz			51.0		

Table D-18. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	12.1	9.6	7.1	4.7	2.2	-0.2
		W	16.2	9.1	5.1	3.0	1.7	1.0
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	66.6	64.1	61.6	59.2	56.7	54.3
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-96.8	-99.3	-101.8	-104.2	-106.7	-109.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5	-84.5	-84.5	-84.5	-84.5
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6	-11.6	-11.6	-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	82.9	80.4	77.9	75.5	73.0	70.6
12.	Satellite System Gain	dB	135.8	135.8	135.8	135.8	135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.7	-0.8	-3.3	-5.7	-8.2	-10.6
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	See Figure 4					
18.	RCV Sys. Noise Temp.	dB/K	See Figure 4					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	51.0	51.0	51.0	51.1	51.1	51.2
21.	Downlink Rec'd. C/I	dB-Hz	77.2	74.7	72.2	69.8	67.3	64.9
22.	System C/N_o (Total)	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0
23.	Required C/N_o	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0

Table D-19. Link Budget for Required C/N_0 = 54.0 dB-Hz for a MESH Network Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	26.4	23.9	20.4	17.9	15.4	13.0	10.5	8.0	3.7
		W	436.5	245.5	109.6	61.7	34.7	20.0	11.2	6.3	2.3
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	69.6	67.1		64.6		62.2		59.7	57.3
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-93.8	-96.3		-98.8		-101.2		-103.7	-106.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5		-84.5		-84.5		-84.5	-84.5
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6		-11.6		-11.6		-11.6	-11.6
11.	Uplink Rec'd. C/N_0	dB-Hz	85.9	83.4		80.9		78.5		76.0	73.6
12.	Satellite System Gain	dB	135.8	135.8		135.8		135.8		135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2		-0.3		-2.7		-5.2	-7.6
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	54.0	54.0		54.0		54.1		54.1	54.2
21.	Downlink Rec'd. C/I	dB-Hz	80.2	77.7		75.2		72.8		70.3	67.9
22.	System C/N_0 (Total)	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0
23.	Required C/N_0	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0

Table D-20. Link Budget for Required C/N_0 = 54.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	12.5	9.0	6.5	4.0	2.1
		W	17.8	7.9	4.5	2.5	1.6
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			55.7		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-107.7		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.5		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-11.6		
11.	Uplink Rec'd. C/N_0	dB-Hz			72.0		
12.	Satellite System Gain	dB			135.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-9.2		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_0	dB-Hz			54.3		
21.	Downlink Rec'd. C/I	dB-Hz			66.3		
22.	System C/N_0 (Total)	dB-Hz			54.0		
23.	Required C/N_0	dB-Hz			54.0		

Table D-21. Link Budget for Required C/N_0 = 54.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	15.1	12.6	10.1	7.7	5.2	2.8
		W	32.4	18.2	10.2	5.9	3.3	1.9
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	69.6	67.1	64.6	62.2	59.7	57.3
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-93.8	-96.3	-98.8	-101.2	-103.7	-106.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5	-84.5	-84.5	-84.5	-84.5
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6	-11.6	-11.6	-11.6	-11.6
11.	Uplink Rec'd. C/N_0	dB-Hz	85.9	83.4	80.9	78.5	76.0	73.6
12.	Satellite System Gain	dB	135.8	135.8	135.8	135.8	135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.7	2.2	-0.3	-2.7	-5.2	-7.6
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	See Figure 4					
18.	RCV Sys. Noise Temp.	dB/K	See Figure 4					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	54.0	54.0	54.0	54.1	54.1	54.2
21.	Downlink Rec'd. C/I	dB-Hz	80.2	77.7	75.2	72.8	70.3	67.9
22.	System C/N_0 (Total)	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0
23.	Required C/N_0	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0

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Table D-22. Link Budget for Required C/N_o = 57.0 dB-Hz for a MESH Network Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	29.4	26.9	23.4	20.9	18.4	16.0	13.5	11.0	6.7
		W	871.0	489.8	218.8	123.0	69.2	39.8	22.4	12.6	4.7
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	72.6	70.1		67.6		65.2		62.7	60.3
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3		-95.8		-98.2		-100.7	-103.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5		-84.5		-84.5		-84.5	-84.5
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6		-11.6		-11.6		-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	88.9	86.4		83.9		81.5		79.0	76.6
12.	Satellite System Gain	dB	135.8	135.8		135.8		135.8		135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.7	5.2		2.7		0.3		-2.2	-4.6
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	------------------------------ See Figure 4 ------------------------------								
18.	RCV Sys. Noise Temp.	dB/K	------------------------------ See Figure 4 ------------------------------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.0	57.0		57.0		57.1		57.1	57.2
21.	Downlink Rec'd. C/I	dB-Hz	83.2	80.7		78.2		75.8		73.3	70.9
22.	System C/N_o (Total)	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0

Table D-23. Link Budget for Required C/N_o = 57.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	15.5	12.0	9.5	7.0	5.1
		W	35.5	15.8	8.9	5.0	3.2
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			58.7		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-104.7		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-84.5		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-11.6		
11.	Uplink Rec'd. C/N_o	dB-Hz			75.0		
12.	Satellite System Gain	dB			135.8		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-6.2		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			57.3		
21.	Downlink Rec'd. C/I	dB-Hz			69.3		
22.	System C/N_o (Total)	dB-Hz			57.0		
23.	Required C/N_o	dB-Hz			57.0		

Table D-24. Link Budget for Required C/N_o = 57.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using an INTELSAT Hemispheric Beam Coverage Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	18.1	15.6	13.1	10.7	8.2	5.8
		W	64.6	36.3	20.4	11.7	6.6	3.8
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	72.6	70.1	67.6	65.2	62.7	60.3
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-90.8	-93.3	-95.8	-98.2	-100.7	-103.1
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-84.5	-84.5	-84.5	-84.5	-84.5	-84.5
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-11.6	-11.6	-11.6	-11.6	-11.6	-11.6
11.	Uplink Rec'd. C/N_o	dB-Hz	88.9	86.4	83.9	81.5	79.0	76.6
12.	Satellite System Gain	dB	135.8	135.8	135.8	135.8	135.8	135.8
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.7	5.2	2.7	0.3	-2.2	-4.6
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	---------------------------- See Figure 4 ----------------------------					
18.	RCV Sys. Noise Temp.	dB/K	---------------------------- See Figure 4 ----------------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.0	57.0	57.0	57.1	57.1	57.2
21.	Downlink Rec'd. C/I	dB-Hz	83.2	80.7	78.2	75.8	73.3	70.9
22.	System C/N_o (Total)	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0

Table D-25. Link Budget for Required C/N_0 = 48.0 dB-Hz for a MESH Network Using a Palapa A Satellite Resource

MESH Network -- Station-to-Station Link Budget

1. Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2. XMTR Pwr. to Ant.	dBW	4.0	1.5	-2.0	-4.4	-6.9	-9.3	-11.8	-14.1	-18.1
	W	2.5	1.4	0.6	0.4	0.2	0.1	0.1	<0.1	<0.1
3. XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4. Uplink EIRP (6 GHz)	dBW	47.2	44.7		42.3		39.9		37.6	35.5
5. Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6. Uplink Prop. Loss ($\alpha=20°$)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7. Pwr. Flux Den. at Sat.	dBW/m^2	-116.2	-118.7		-121.1		-123.5		-125.8	-127.9
8. Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0		-93.0		-93.0		-93.0	-93.0
9. Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10. Satellite G/T	dB/K	-7.0	-7.0		-7.0		-7.0		-7.0	-7.0
11. Uplink Rec'd. C/N_0	dB-Hz	68.1	65.6		63.2		60.8		58.5	56.4
12. Satellite System Gain	dB	152.3	152.3		152.3		152.3		152.3	152.3
13. Sat. EIRP per Carrier (4 GHz)	dBW	-1.2	-3.7		-6.1		-8.5		-10.8	-12.9
14. Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15. Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16. Downlink Prop. Loss ($\alpha=20°$)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17. RCV Ant. Gain	dB	--------------------------------- See Figure 4 ---------------------------------								
18. RCV Sys. Noise Temp.	dB/K	--------------------------------- See Figure 4 ---------------------------------								
19. Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20. Downlink Rec'd. C/N_0	dB-Hz	48.1	48.1		48.2		48.3		48.5	48.9
21. Downlink Rec'd. C/I	dB-Hz	74.3	71.8		69.4		67.0		64.7	62.6
22. System C/N_0 (Total)	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0
23. Required C/N_0	dB-Hz	48.0	48.0		48.0		48.0		48.0	48.0

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Table D-26. Link Budget for Required C/N_o = 48.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using a Palapa A Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	-9.1	-12.6	-15.1	-17.6	-19.5
		W	0.1	0.1	<0.1	<0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			34.1		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-129.3		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-93.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-7.0		
11.	Uplink Rec'd. C/N_o	dB-Hz			55.0		
12.	Satellite System Gain	dB			152.3		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-14.3		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			49.2		
21.	Downlink Rec'd. C/I	dB-Hz			61.2		
22.	System C/N_o (Total)	dB-Hz			48.0		
23.	Required C/N_o	dB-Hz			48.0		

Table D-27. Link Budget for Required C/N_0 = 48.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using a Palapa A Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	-7.3	-9.8	-12.2	-14.6	-16.9	-19.0
		W	0.2	0.1	0.1	<0.1	<0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	47.2	44.7	42.3	39.9	37.6	35.5
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-116.2	-118.7	-121.1	-123.5	-125.8	-127.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0	-93.0	-93.0	-93.0	-93.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
11.	Uplink Rec'd. C/N_0	dB-Hz	68.1	65.6	63.2	60.8	58.5	56.4
12.	Satellite System Gain	dB	152.3	152.3	152.3	152.3	152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	-1.2	-3.7	-6.1	-8.5	-10.8	-12.9
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------					
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	48.1	48.1	48.2	48.3	48.5	48.9
21.	Downlink Rec'd. C/I	dB-Hz	74.3	71.8	69.4	67.0	64.7	62.6
22.	System C/N_0 (Total)	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0
23.	Required C/N_0	dB-Hz	48.0	48.0	48.0	48.0	48.0	48.0

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Table D-28. Link Budget for Required C/N_0 = 51.0 dB-Hz for a MESH Network Using a Palapa A Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	7.0	4.5	1.0	-1.4	-3.9	-6.3	-8.8	-11.1	-15.1
		W	5.0	2.8	1.3	0.7	0.4	0.2	0.1	0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	50.2	47.7		45.3		42.9		40.6	38.5
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-113.2	-115.7		-118.1		-120.5		-122.8	-124.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0		-93.0		-93.0		-93.0	-93.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0		-7.0		-7.0		-7.0	-7.0
11.	Uplink Rec'd. C/N_0	dB-Hz	71.1	68.6		66.2		63.8		61.5	59.4
12.	Satellite System Gain	dB	152.3	152.3		152.3		152.3		152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.8	-0.7		-3.1		-5.5		-7.8	-9.9
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	51.1	51.1		51.2		51.3		51.5	51.9
21.	Downlink Rec'd. C/I	dB-Hz	77.3	74.8		72.4		70.0		67.7	65.6
22.	System C/N_0 (Total)	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0
23.	Required C/N_0	dB-Hz	51.0	51.0		51.0		51.0		51.0	51.0

Table D-29. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using a Palapa A Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	-6.1	-9.6	-12.1	-14.6	-16.5
		W	0.2	0.1	0.1	<0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			37.1		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-126.3		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-93.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-7.0		
11.	Uplink Rec'd. C/N_o	dB-Hz			58.0		
12.	Satellite System Gain	dB			152.3		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-11.3		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			52.2		
21.	Downlink Rec'd. C/I	dB-Hz			64.2		
22.	System C/N_o (Total)	dB-Hz			51.0		
23.	Required C/N_o	dB-Hz			51.0		

Table D-30. Link Budget for Required C/N_o = 51.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using a Palapa A Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	-4.3	-6.8	-9.2	-11.6	-13.9	-16.0
		W	0.4	0.2	0.1	0.1	<0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	50.2	47.7	45.3	42.9	40.6	38.5
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-113.2	-115.7	-118.1	-120.5	-122.8	-124.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0	-93.0	-93.0	-93.0	-93.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
11.	Uplink Rec'd. C/N_o	dB-Hz	71.1	68.6	66.2	63.8	61.5	59.4
12.	Satellite System Gain	dB	152.3	152.3	152.3	152.3	152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	1.8	-0.7	-3.1	-5.5	-7.8	-9.9
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	----------------------- See Figure 4 -----------------------					
18.	RCV Sys. Noise Temp.	dB/K	----------------------- See Figure 4 -----------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	51.1	51.1	51.2	51.3	51.5	51.9
21.	Downlink Rec'd. C/I	dB-Hz	77.3	74.8	72.4	70.0	67.7	65.6
22.	System C/N_o (Total)	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0
23.	Required C/N_o	dB-Hz	51.0	51.0	51.0	51.0	51.0	51.0

Table D-31. Link Budget for Required C/N_o = 54.0 dB-Hz for a MESH Network Using a Palapa A Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	10.0	7.5	4.0	1.6	-0.9	-3.3	-5.8	-8.1	-12.1
		W	10.0	5.6	2.5	1.4	0.8	0.5	0.3	0.2	0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	53.2	50.7		48.3		45.9		43.6	41.5
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-110.2	-112.7		-115.1		-117.5		-119.8	-121.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0		-93.0		-93.0		-93.0	-93.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0		-7.0		-7.0		-7.0	-7.0
11.	Uplink Rec'd. C/N_o	dB-Hz	74.1	71.6		69.2		66.8		64.5	62.4
12.	Satellite System Gain	dB	152.3	152.3		152.3		152.3		152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.8	2.3		-0.1		-2.5		-4.8	-6.9
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------								
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	54.1	54.1		54.2		54.3		54.5	54.9
21.	Downlink Rec'd. C/I	dB-Hz	80.3	77.8		75.4		73.0		70.7	68.6
22.	System C/N_o (Total)	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0
23.	Required C/N_o	dB-Hz	54.0	54.0		54.0		54.0		54.0	54.0

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Table D-32. Link Budget for Required C/N_o = 54.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using a Palapa A Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	-3.1	-6.6	-9.1	-11.6	-13.5
		W	0.5	0.2	0.1	0.1	<0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			40.1		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-123.3		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-93.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-7.0		
11.	Uplink Rec'd. C/N_o	dB-Hz			61.0		
12.	Satellite System Gain	dB			152.3		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-8.3		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_o	dB-Hz			55.2		
21.	Downlink Rec'd. C/I	dB-Hz			67.2		
22.	System C/N_o (Total)	dB-Hz			54.0		
23.	Required C/N_o	dB-Hz			54.0		

Table D-33. Link Budget for Required C/N_0 = 54.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using a Palapa A Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	-1.3	-3.8	-6.2	-8.6	-10.9	-13.0
		W	0.7	0.4	0.2	0.1	0.1	0.1
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	53.2	50.7	48.3	45.9	43.6	41.5
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-110.2	-112.7	-115.1	-117.5	-119.8	-121.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0	-93.0	-93.0	-93.0	-93.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
11.	Uplink Rec'd. C/N_0	dB-Hz	74.1	71.6	69.2	66.8	64.5	62.4
12.	Satellite System Gain	dB	152.3	152.3	152.3	152.3	152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	4.8	2.3	-0.1	-2.5	-4.8	-6.9
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	------------------ See Figure 4 ------------------					
18.	RCV Sys. Noise Temp.	dB/K	------------------ See Figure 4 ------------------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_0	dB-Hz	54.1	54.1	54.2	54.3	54.5	54.9
21.	Downlink Rec'd. C/I	dB-Hz	80.3	77.8	75.4	73.0	70.7	68.6
22.	System C/N_0 (Total)	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0
23.	Required C/N_0	dB-Hz	54.0	54.0	54.0	54.0	54.0	54.0

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Table D-34. Link Budget for Required C/N_o = 57.0 dB-Hz for a MESH Network Using a Palapa A Satellite Resource

MESH Network -- Station-to-Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
	Antenna Diameter	m	3.0	3.0	4.5	4.5	6.0	6.0	8.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	13.0	10.5	7.0	4.6	2.1	-0.3	-2.8	-5.1	-9.1
		W	20.0	11.2	5.0	2.9	1.6	0.9	0.5	0.3	0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	43.2	46.7	46.7	49.2	49.2	51.7	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW	56.2	53.7		51.3		48.9		46.6	44.5
5.	Misc. Uplink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2		200.2		200.2		200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-107.2	-109.7		-112.1		-114.5		-116.8	-118.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0		-93.0		-93.0		-93.0	-93.0
9.	Boltzmann's Constant	dBW/K-Hz	-228.6	-228.6		-228.6		-228.6		-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0		-7.0		-7.0		-7.0	-7.0
11.	Uplink Rec'd. C/N_o	dB-Hz	77.1	74.6		72.2		69.8		67.5	65.4
12.	Satellite System Gain	dB	152.3	152.3		152.3		152.3		152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.8	5.3		2.9		0.5		-1.8	-3.9
14.	Sat. Int. Power	dBW/Hz	-76.0	-76.0		-76.0		-76.0		-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5		0.5		0.5		0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3		196.3		196.3		196.3	196.3
17.	RCV Ant. Gain	dB	------------------------------ See Figure 4 ------------------------------								
18.	RCV Sys. Noise Temp.	dB/K	------------------------------ See Figure 4 ------------------------------								
19.	Earth Station G/T	dB/K	17.5	20.0		22.5		25.0		27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.1	57.1		57.2		57.3		57.5	57.9
21.	Downlink Rec'd. C/I	dB-Hz	83.3	80.8		78.4		76.0		73.7	71.6
22.	System C/N_o (Total)	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0		57.0		57.0		57.0	57.0

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Table D-35. Link Budget for Required C/N_0 = 57.0 dB-Hz for a STAR Network, Remote Station-to-Central Station Link, Using a Palapa A Satellite Resource

STAR Network -- Remote Station-to-Central Station Link Budget

1.	Antenna Diameter	m	3.0	4.5	6.0	8.0	10.0
2.	XMTR Pwr. to Ant.	dBW	-0.1	-3.6	-6.1	-8.6	-10.5
		W	1.0	0.4	0.2	0.1	0.1
3.	XMTR Ant. Gain (6 GHz)	dB	43.2	46.7	49.2	51.7	53.6
4.	Uplink EIRP (6 GHz)	dBW			43.1		
5.	Misc. Uplink Losses	dB			0.5		
6.	Uplink Prop. Loss (α=20°)	dB			200.2		
7.	Pwr. Flux Den. at Sat.	dBW/m^2			-120.3		
8.	Multi-Carrier Operating Flux Density	dBW/m^2			-93.0		
9.	Boltzmann's Constant	dBW/K-Hz			-228.6		
10.	Satellite G/T	dB/K			-7.0		
11.	Uplink Rec'd. C/N_0	dB-Hz			64.0		
12.	Satellite System Gain	dB			152.3		
13.	Sat. EIRP per Carrier (4 GHz)	dBW			-5.3		
14.	Sat. Int. Pwr.	dB-Hz			-76.0		
15.	Misc. Downlink Losses	dB			0.5		
16.	Downlink Prop. Loss (α=20°)	dB			196.3		
17.	RCV Ant. Gain	dB			STD "B"		
18.	RCV Sys. Noise Temp.	dB/K			STD "B"		
19.	Earth Station G/T (Std "B")	dB/K			31.7		
20.	Downlink Rec'd. C/N_0	dB-Hz			58.2		
21.	Downlink Rec'd. C/I	dB-Hz			70.2		
22.	System C/N_0 (Total)	dB-Hz			57.0		
23.	Required C/N_0	dB-Hz			57.0		

Table D-36. Link Budget for Required C/N_o = 57.0 dB-Hz for a STAR Network, Central Station-to-Remote Station Link, Using a Palapa A Satellite Resource

STAR Network -- Central Station-to-Remote Station Link Budget

1.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
2.	XMTR Pwr. to Ant.	dBW	1.7	-0.8	-3.2	-5.6	-7.9	-10.0
		W	1.5	0.8	0.5	0.3	0.2	0.1
3.	XMTR Ant. Gain (6 GHz)	dB	54.5	54.5	54.5	54.5	54.5	54.5
4.	Uplink EIRP (6 GHz)	dBW	56.2	53.7	51.3	48.9	46.6	44.5
5.	Misc. Uplink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
6.	Uplink Prop. Loss (α=20°)	dB	200.2	200.2	200.2	200.2	200.2	200.2
7.	Pwr. Flux Den. at Sat.	dBW/m^2	-107.2	-109.7	-112.1	-114.5	-116.8	-118.9
8.	Multi-Carrier Operating Flux Density	dBW/m^2	-93.0	-93.0	-93.0	-93.0	-93.0	-93.0
9.	Boltzmann's Constant	dBW/K	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
10.	Satellite G/T	dB/K	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
11.	Uplink Rec'd. C/N_o	dB-Hz	77.1	74.6	72.2	69.8	67.5	65.4
12.	Satellite System Gain	dB	152.3	152.3	152.3	152.3	152.3	152.3
13.	Sat. EIRP per Carrier (4 GHz)	dBW	7.8	5.3	2.9	0.5	-1.8	-3.9
14.	Sat. Int. Pwr.	dBW/Hz	-76.0	-76.0	-76.0	-76.0	-76.0	-76.0
15.	Misc. Downlink Losses	dB	0.5	0.5	0.5	0.5	0.5	0.5
16.	Downlink Prop. Loss (α=20°)	dB	196.3	196.3	196.3	196.3	196.3	196.3
17.	RCV Ant. Gain	dB	---------- See Figure 4 ----------					
18.	RCV Sys. Noise Temp.	dB/K	---------- See Figure 4 ----------					
19.	Earth Station G/T	dB/K	17.5	20.0	22.5	25.0	27.5	30.0
20.	Downlink Rec'd. C/N_o	dB-Hz	57.1	57.1	57.2	57.3	57.5	57.9
21.	Downlink Rec'd. C/I	dB-Hz	83.3	80.8	78.4	76.0	73.7	71.6
22.	System C/N_o (Total)	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0
23.	Required C/N_o	dB-Hz	57.0	57.0	57.0	57.0	57.0	57.0

The satellite EIRP per carrier (downlink at 4 GHz, nominally), shown as item 13 in each of the link budgets, is used to calculate the number of telephone channels that can be supported by 1/4 transponder for each satellite resource, parametric in each station figure of merit, G/T, assuming each of the carrier-to-noise-power-density ratios used in this analysis and one and two channels per carrier. These results are plotted in Figures D-1 through D-5 for an INTELSAT global beam coverage resource, in Figures D-6 through D-10 for an INTELSAT hemispheric beam coverage resource, and in Figures D-11 through D-15 for a Palapa A resource.

In a MESH network where all earth stations are designed with equal figure-of-merit capabilities, the number of possible telephone circuits would be half the number of channels, since two channels are required for each duplex circuit. In a STAR network, communications are always between a remote earth station, assumed in this analysis to have $17.5 \leq G/T \leq 30.0$ dB/K , and the central earth station, assumed to be an INTELSAT Standard B or equivalent capability; i.e., G/T = 31.7 dB/K. One must use the appropriate curves for the remote and central earth stations to determine the number of duplex circuits that can be supported by 1/4 transponder. For an example, refer to Figure D-3 for an INTELSAT global beam coverage satellite and C/N_0 = 54.0 dB-Hz. Assume G/T = 25.0 dB/K for the remote earth station. We see that 21 channels received by the remote earth station require 81% of the available satellite power. Twenty-one channels received by the central earth station require 19% of the available satellite EIRP. Therefore, 1/4 transponder on an INTELSAT global beam coverage satellite will provide 21 duplex telephone circuits in a STAR network when G/T = 25.0 dB/K for the remote earth station.

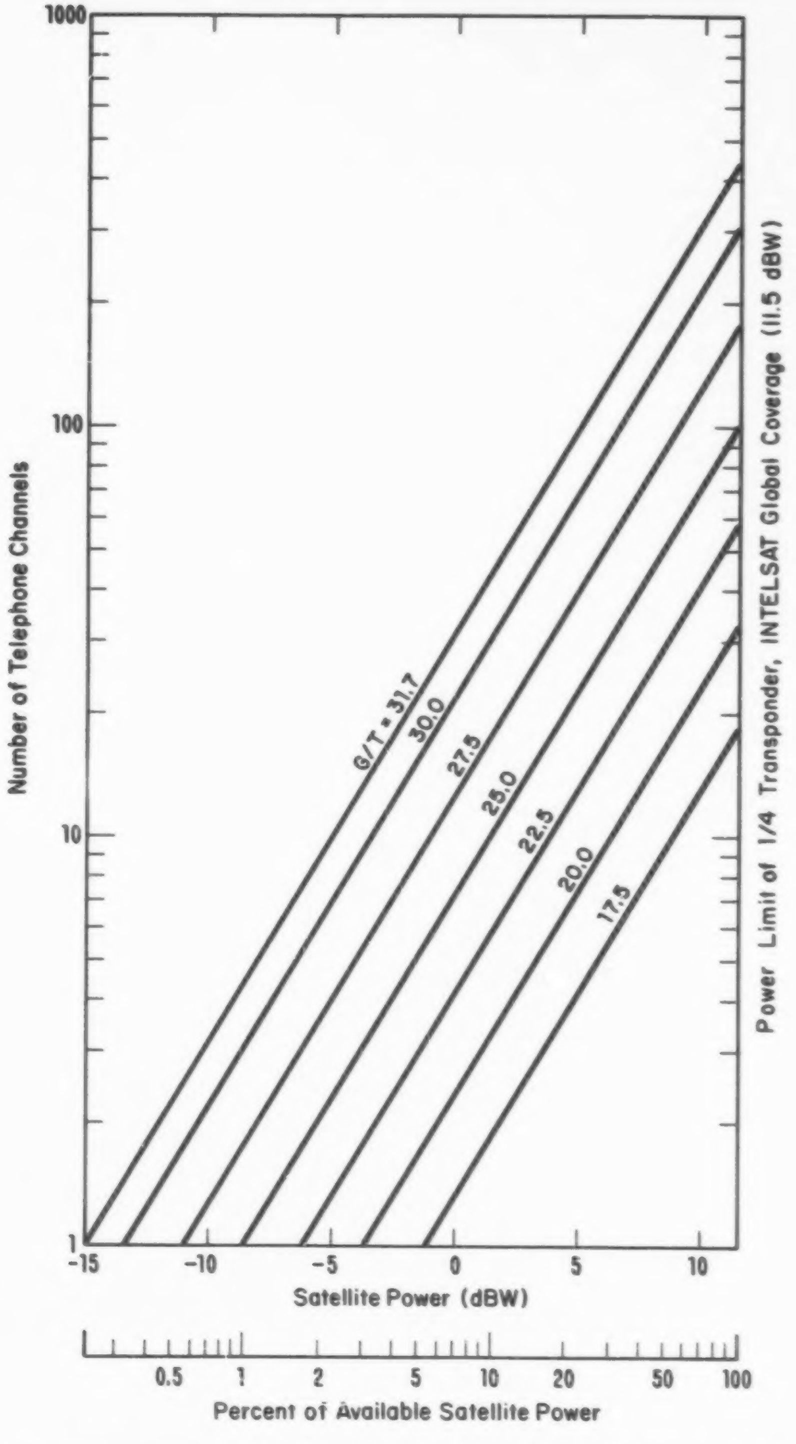

Figure D-1. Curves, parametric in receiving earth station figure of merit G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 48.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW (14.1 W), 1/4 transponder for INTELSAT global beam coverage.

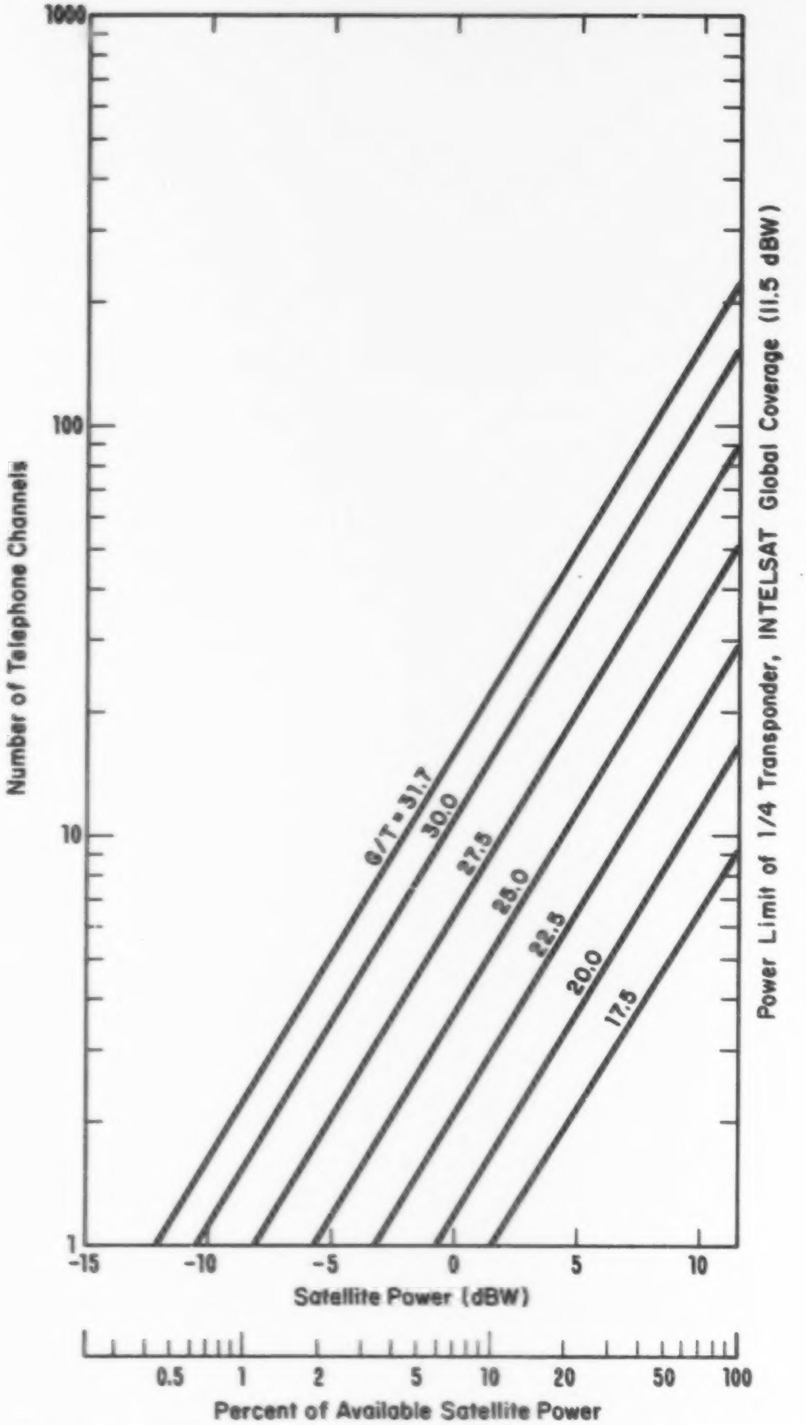

Figure D-2. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 51.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW (14.1 W), 1/4 transponder for INTELSAT global beam coverage.

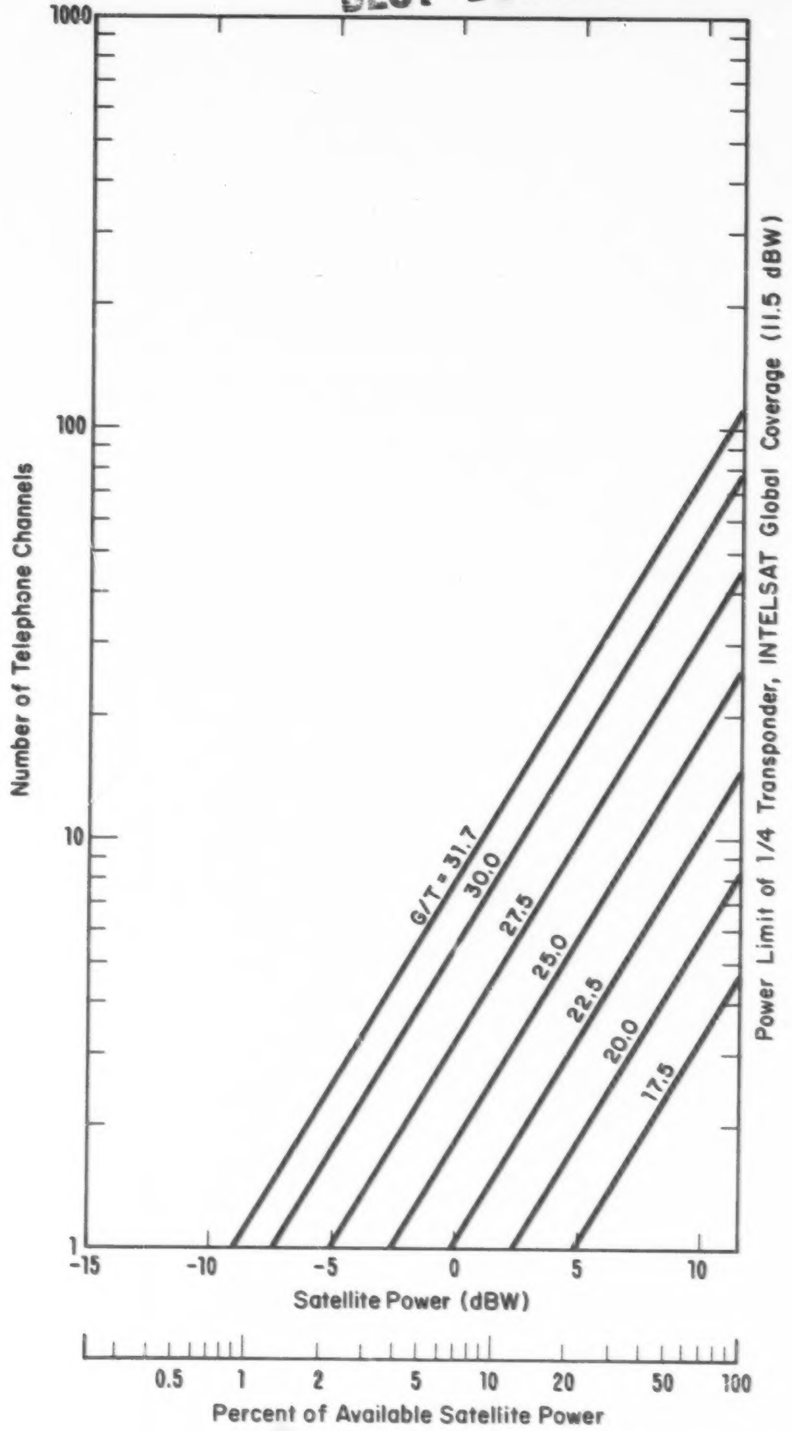

Figure D-3. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing $C/N_0 = 54.0$ dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW (14.1 W), 1/4 transponder for INTELSAT global beam coverage.

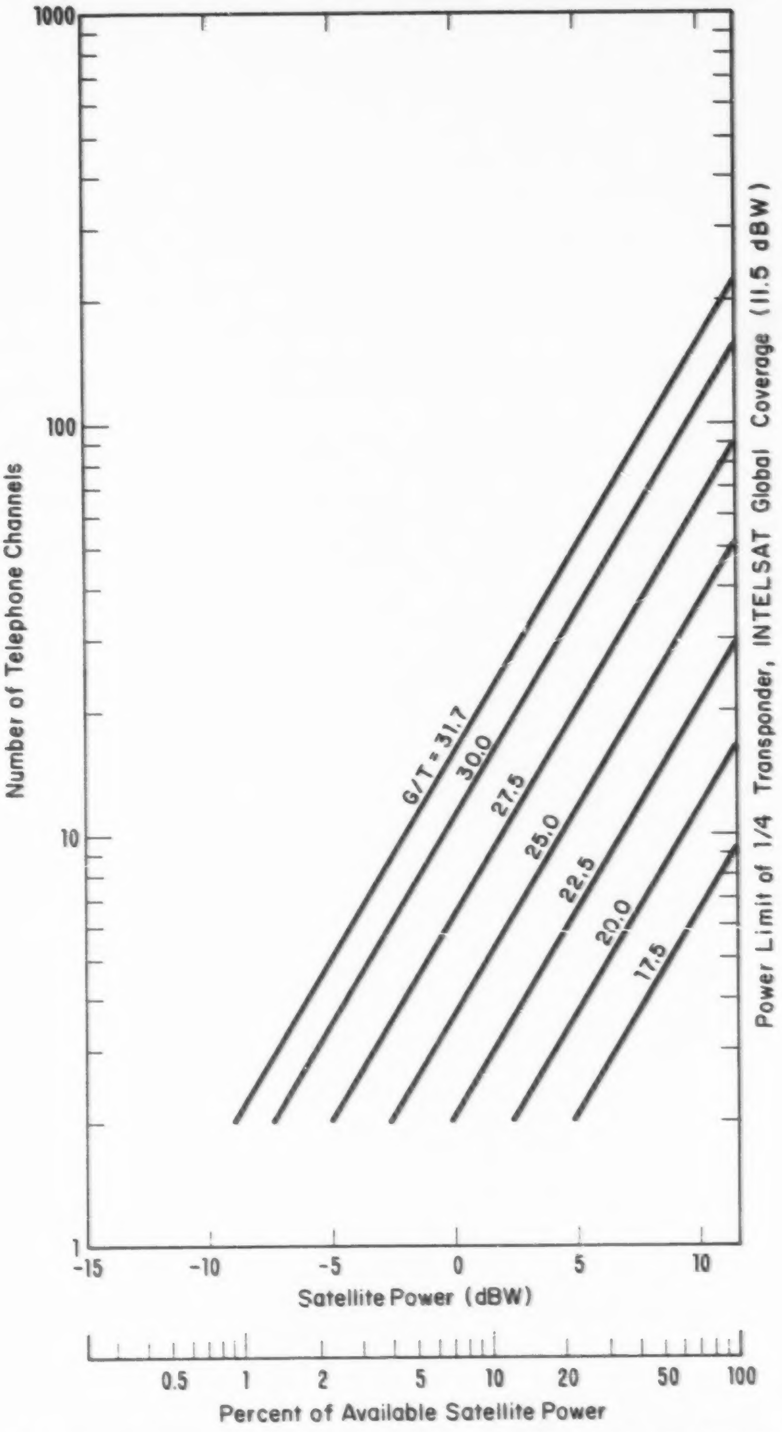

Figure D-4. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using two channels per carrier) providing C/N_o = 54.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW (14.1 W), 1/4 transponder for INTELSAT global beam coverage.

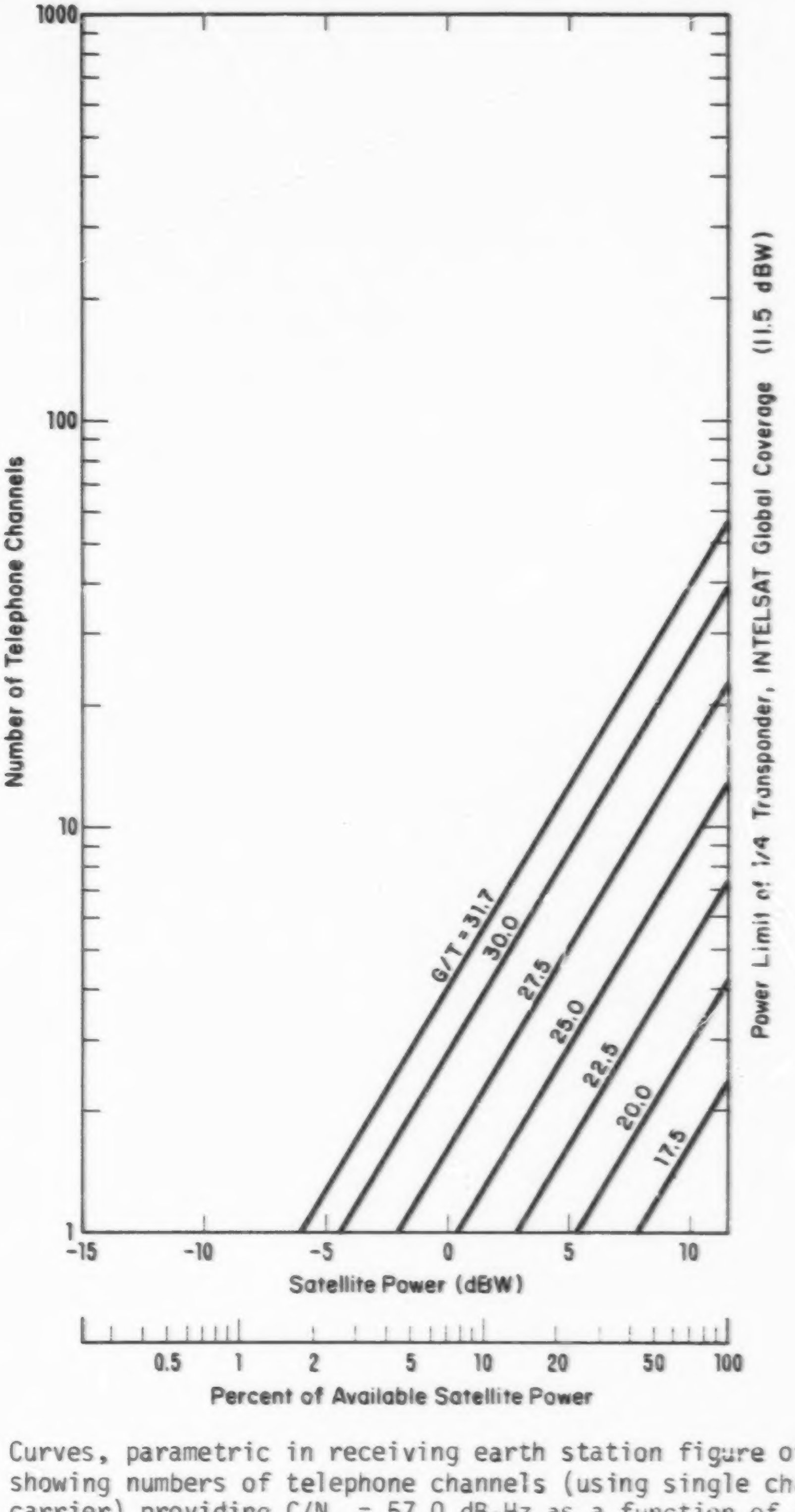

Figure D-5. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 57.0 dB-Hz as a function of available transponder power (EIRP) up to 11.5 dBW (14.1 W), 1/4 transponder for INTELSAT global beam coverage.

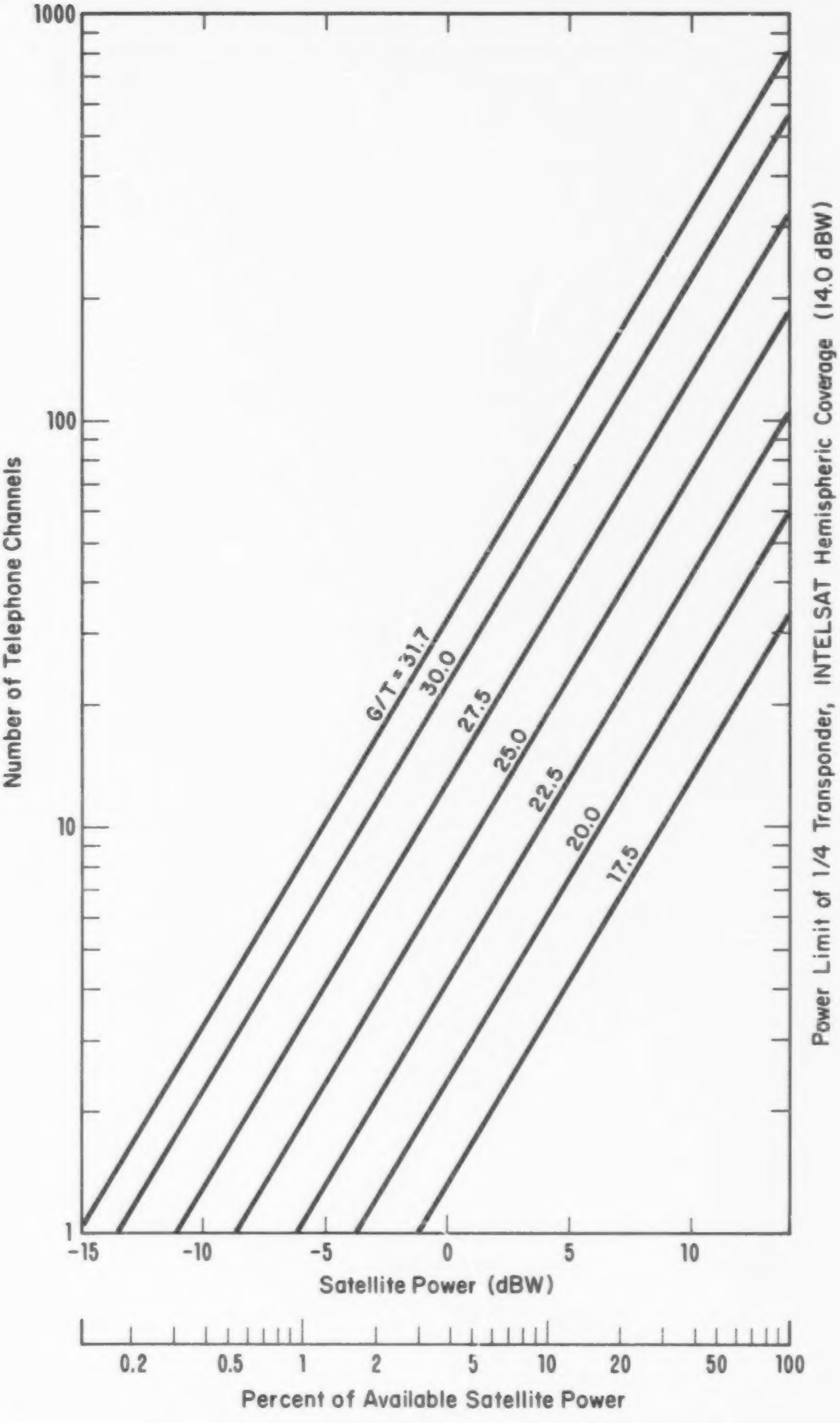

Figure D-6. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 48.0 dB-Hz as a function of available transponder power (EIRP) up to 14.0 dBW (25.1 W), 1/4 transponder for INTELSAT hemispheric beam coverage.

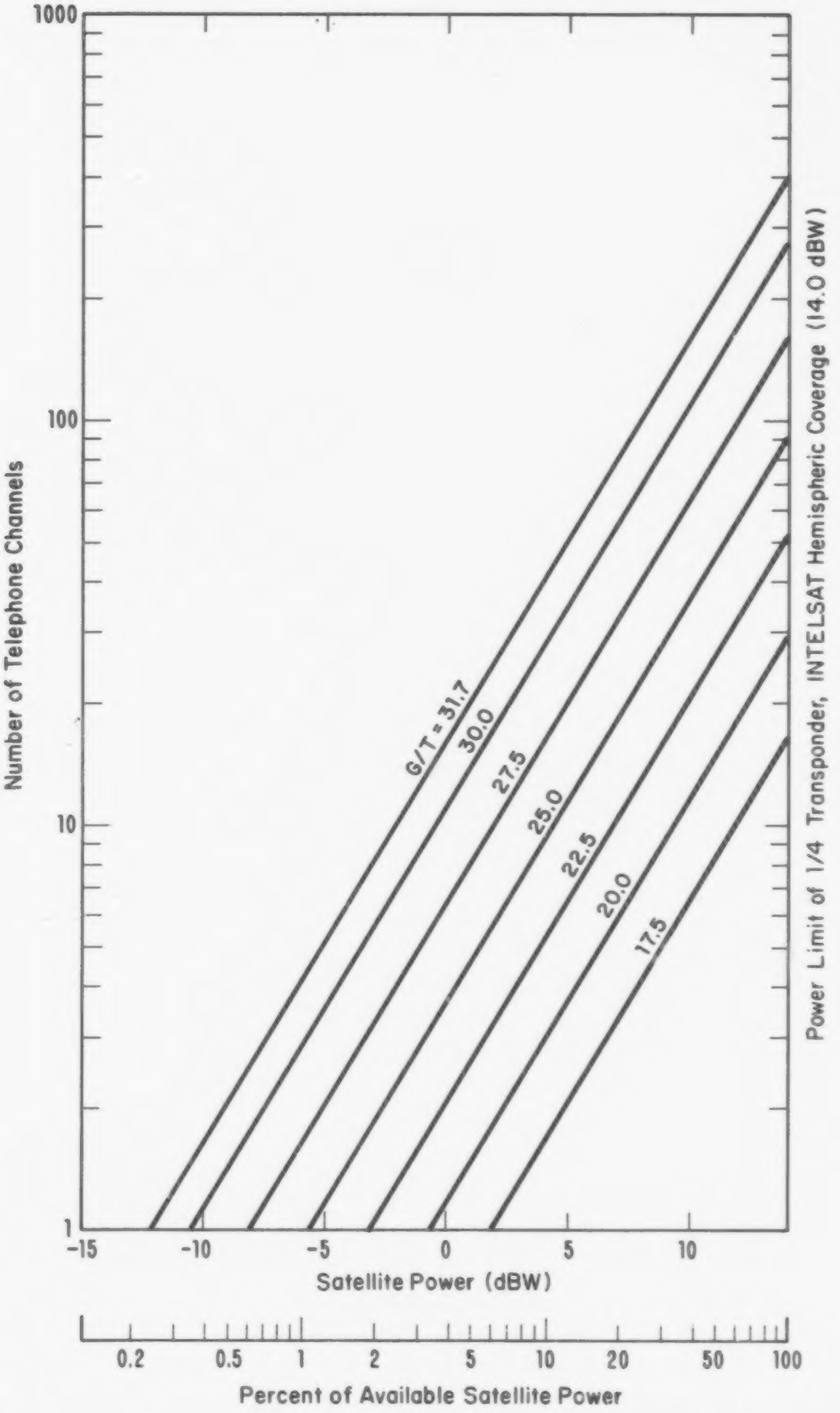

Figure D-7. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 51.0 dB-Hz as a function of available transponder power (EIRP) up to 14.0 dBW (25.1 W), 1/4 transponder for INTELSAT hemispheric beam coverage.

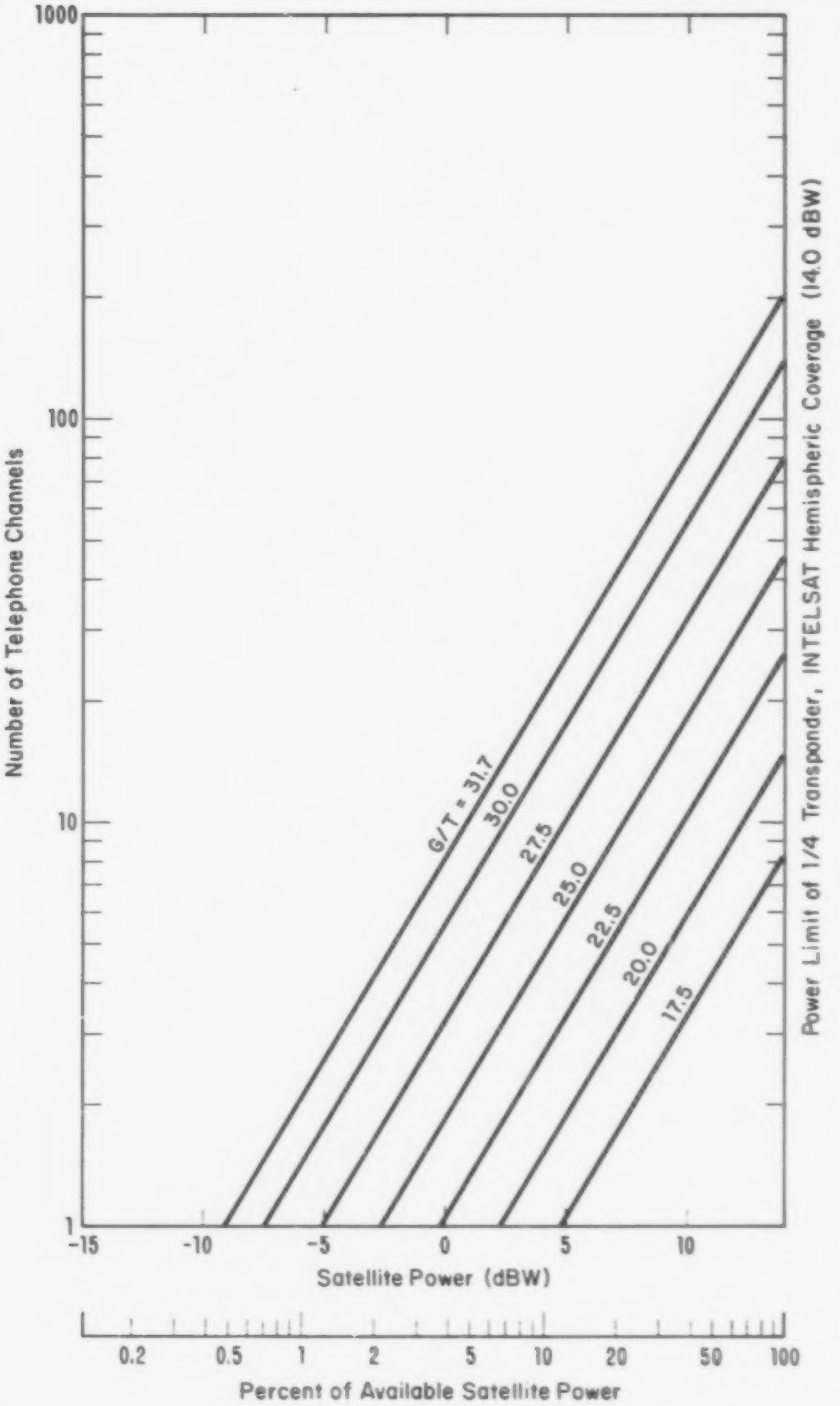

Figure D-8. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 54.0 dB-Hz as a function of available transponder power (EIRP) up to 14.0 dBW (25.1 W), 1/4 transponder for INTELSAT hemispheric beam coverage.

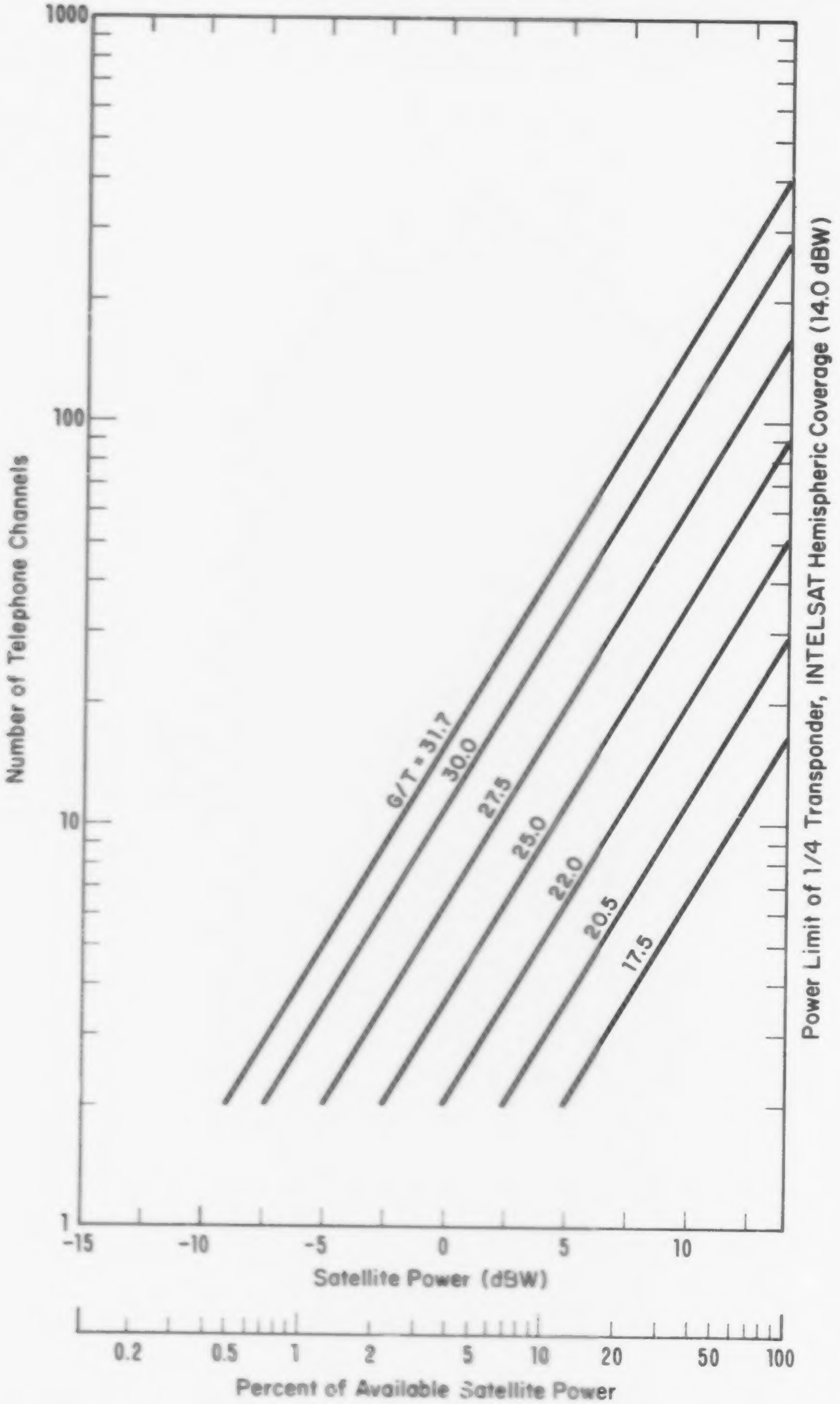

Figure D-9. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using two channels per carrier) providing C/N_0 = 54.0 dB-Hz as a function of available transponder power (EIRP) up to 14.0 dBW (25.1 W), 1/4 transponder for INTELSAT hemispheric beam coverage.

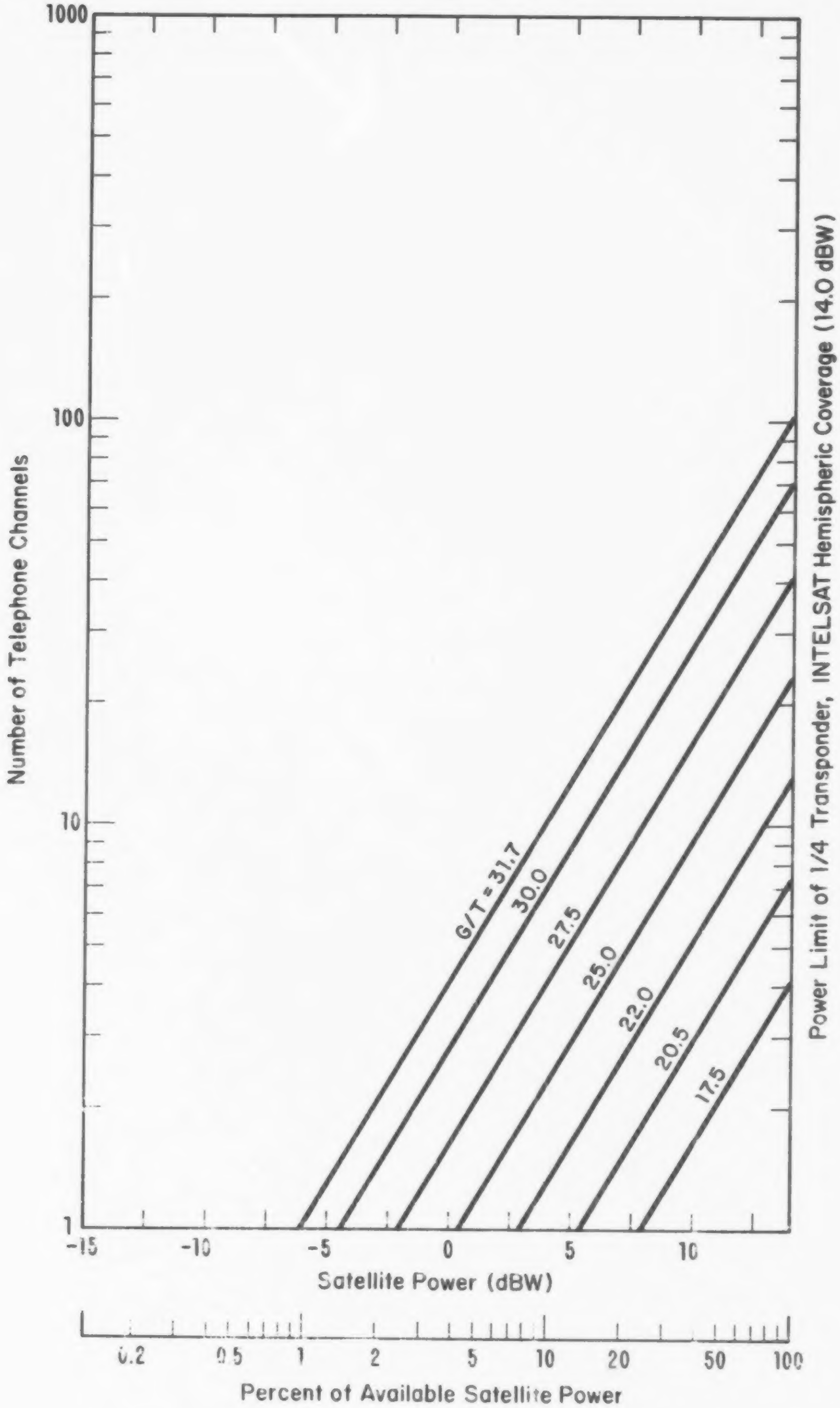

Figure D-10. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 57.0 dB-Hz as a function of available transponder power (EIRP) up to 14.0 dBW (25.1 W), 1/4 transponder for INTELSAT hemispheric beam coverage.

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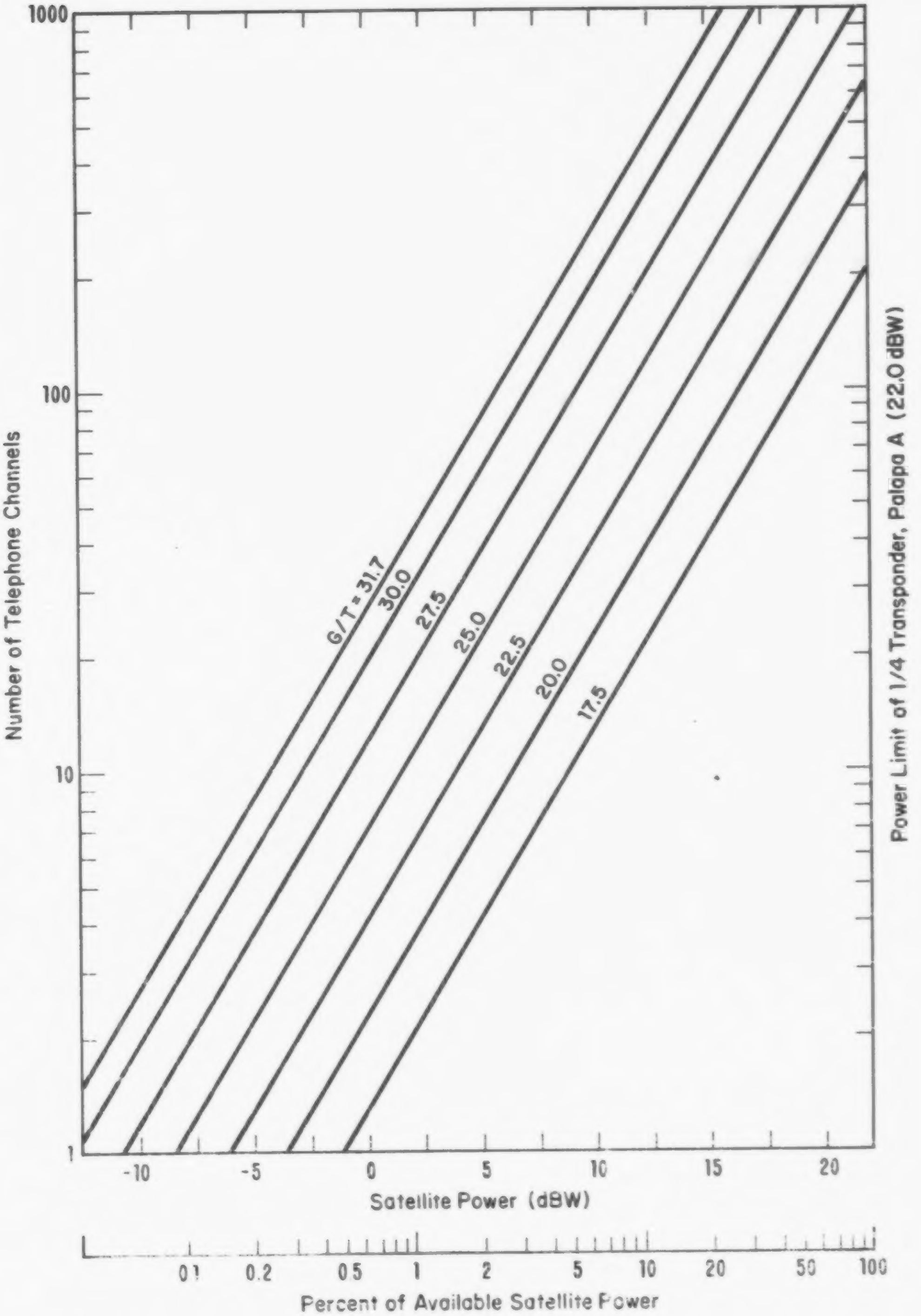

Figure D-11. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 48.0 dB-Hz as a function of available transponder power (EIRP) up to 22.0 dBW (158.5 W), 1/4 transponder for Palapa A.

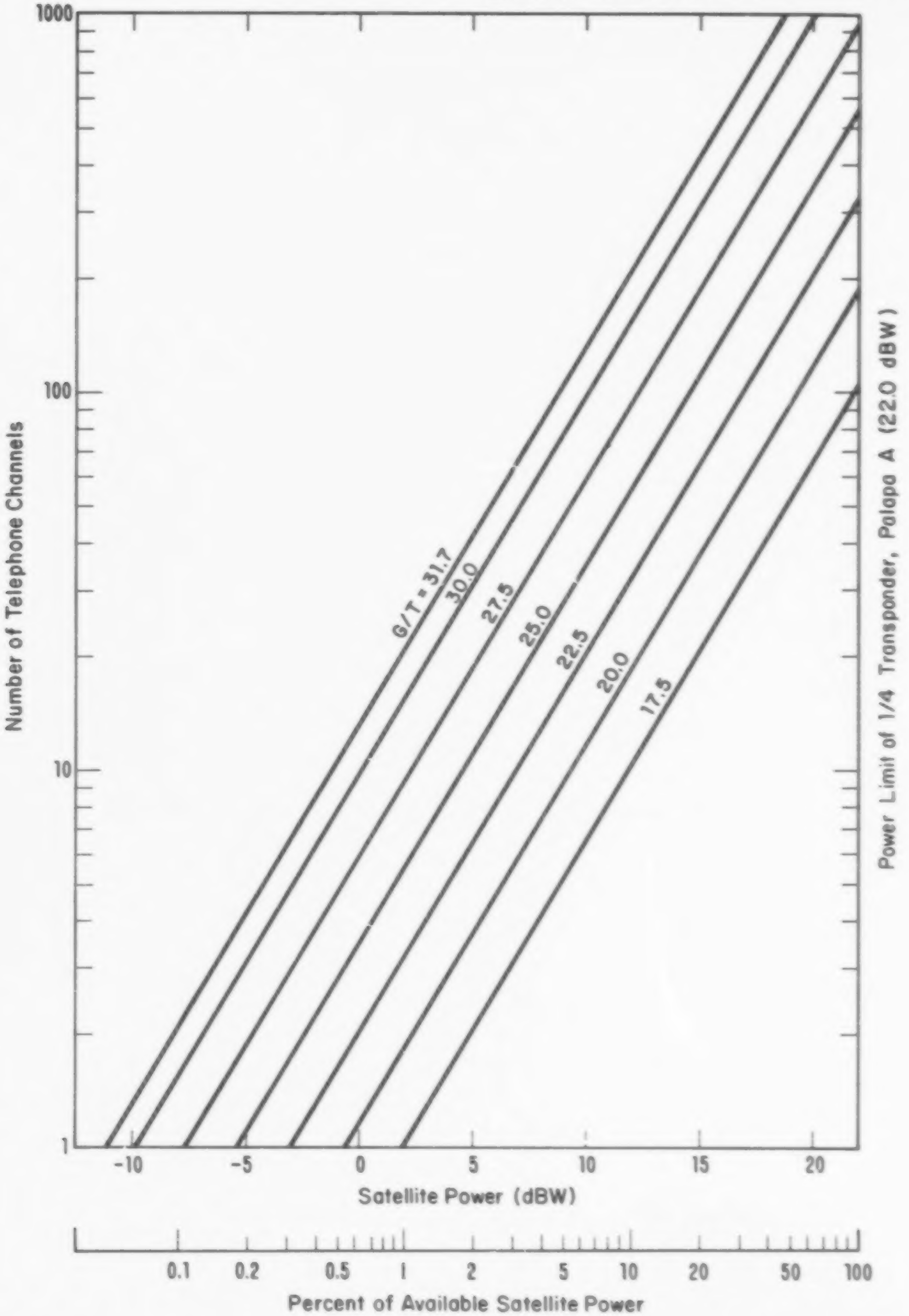

Figure D-12. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 51.0 dB-Hz as a function of available transponder power (EIRP) up to 22.0 dBW (158.5 W), 1/4 transponder for Palapa A.

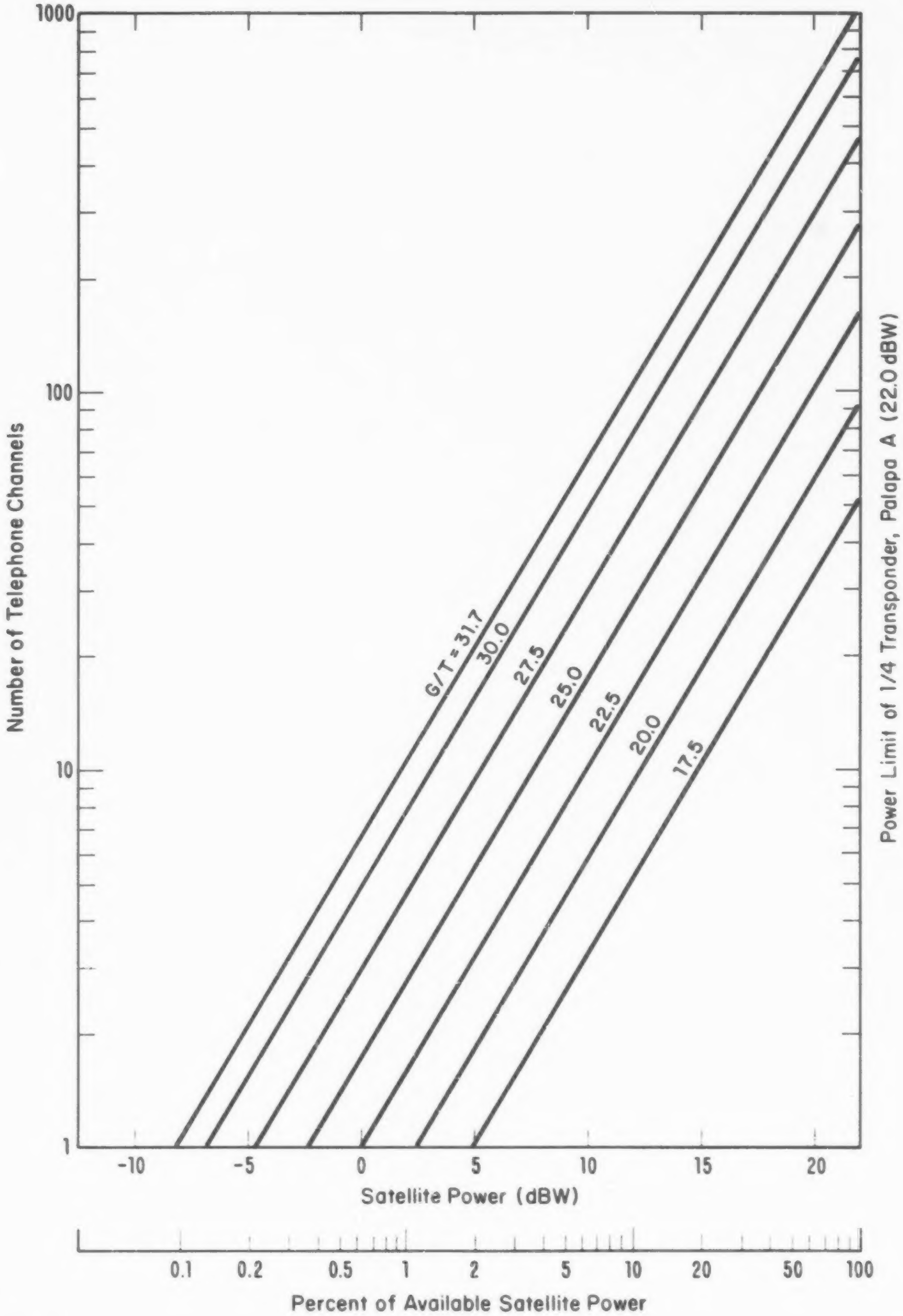

Figure D-13. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 54.0 dB-Hz as a function of available transponder power (EIRP) up to 22.0 dBW (158.5 W), 1/4 transponder for Palapa A.

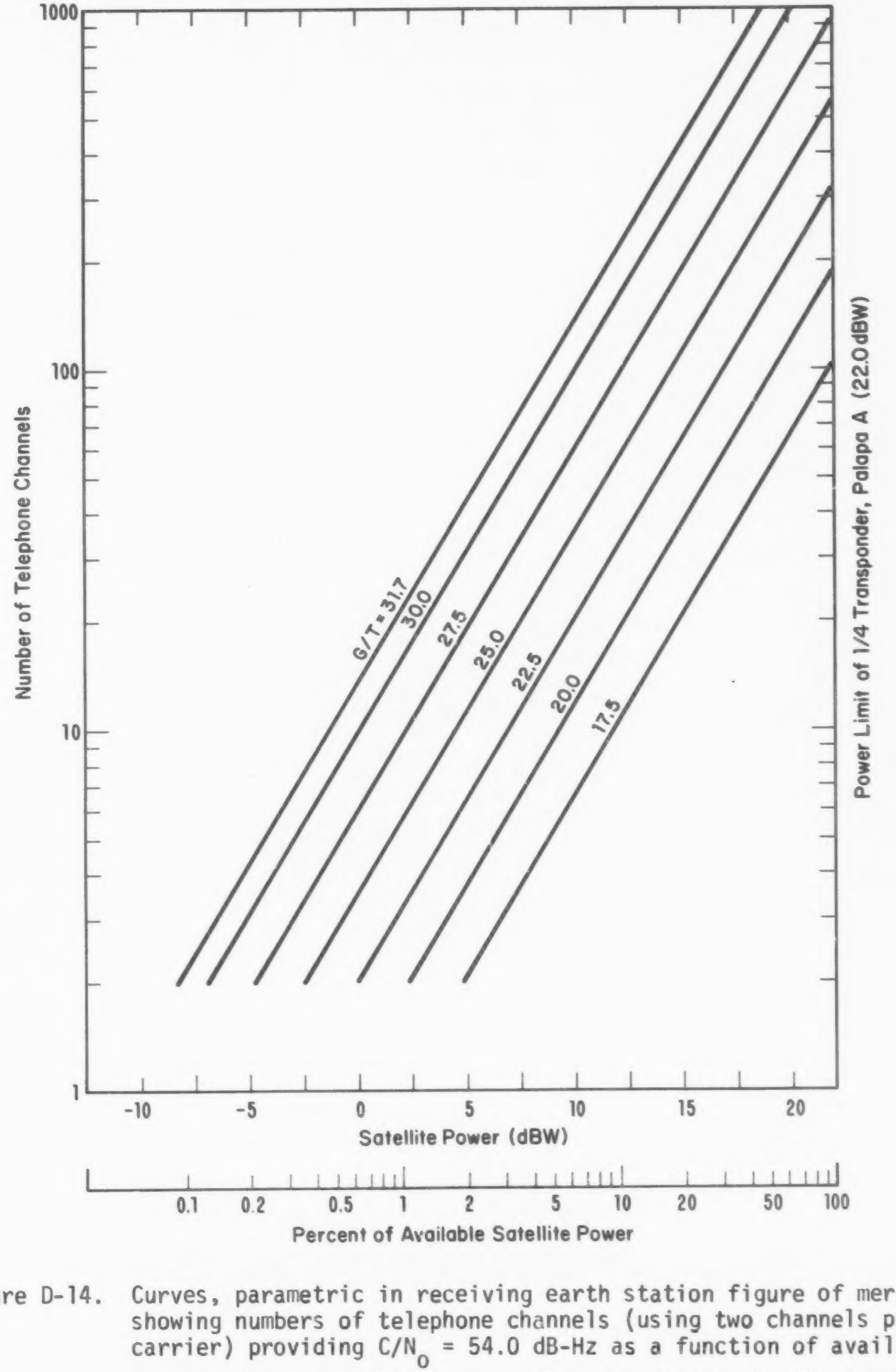

Figure D-14. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using two channels per carrier) providing C/N_0 = 54.0 dB-Hz as a function of available transponder power (EIRP) up to 22.0 dBW (158.5 W), 1/4 transponder for Palapa A.

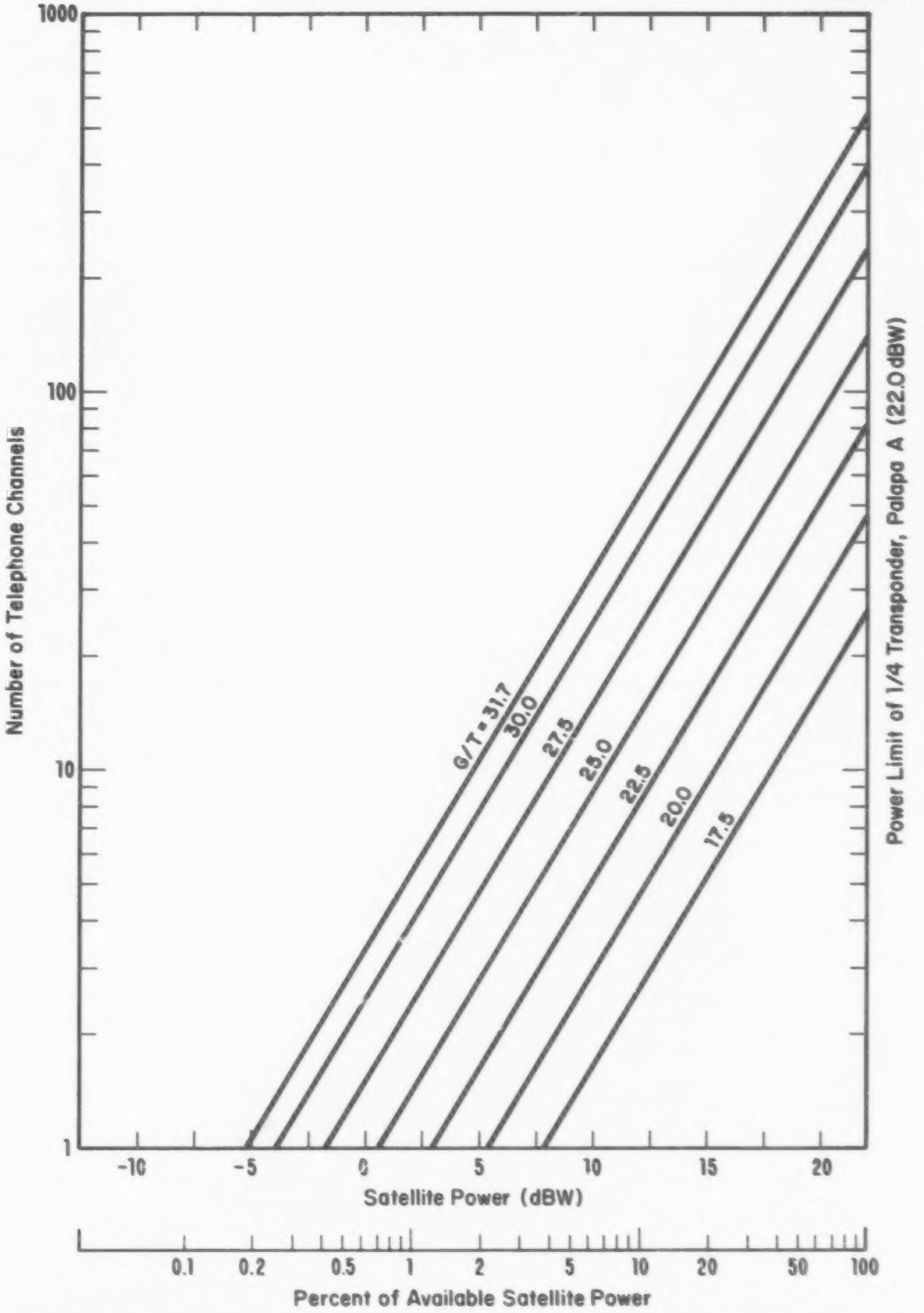

Figure D-15. Curves, parametric in receiving earth station figure of merit (G/T), showing numbers of telephone channels (using single channel per carrier) providing C/N_0 = 57.0 dB-Hz as a function of available transponder power (EIRP) up to 22.0 dBW (158.5 W), 1/4 transponder for Palapa A.

APPENDIX E: TELEPHONE TRAFFIC ANALYSIS

A collection of earth stations for satellite communications which provide rural telephone service according to requirements for the Rural Satellite Program (RSP) (sponsored by the Agency for International Development), form a single communications network. The network is termed a simple network because the network switching requirements are expected to be quite simple. Furthermore, certain assumptions are made, and are discussed later in this appendix, which simplify the analytical detail.

One of the simplifying assumptions is that each earth station serves a finite number of subscribers (telephones). In fact, we assume numbers of ten and twenty subscribers in the analyses. The number of subscribers and the frequency and duration of circuit use by each subscriber are necessary items of information in order to determine use of the network. This use normally is termed density of traffic or traffic intensity and is expressed as a non-dimensional quantity in the international unit, Erlang (Erl). (The Erlang as a traffic density unit is named after A. K. Erlang, the founder of telephone traffic theory.) The numerical value of this quantity indicates the average number of calls which exist simultaneously. In switching network terminology, the numerical value indicates the average number of trunks which are busy at the same time. When aggregated telephone traffic keeps a trunk busy all the time, the traffic intensity is 1 Erl. Or when the traffic intensity is one call-hour per hour, one call-minute per minute, etc., the traffic intensity is 1 Erl.

Other simplifying assumptions which have been made include the following:

-- The network may be MESH or STAR, but it provides capability for each earth station to establish connection with every other earth station in the network. In a MESH network each station can link directly with every other station; in a STAR network the linking must be established through the central station, and these results apply only to the remote earth stations. The number of available circuits will determine the number of stations in the network which can link simultaneously.

-- Each earth station will serve 10 or 20 subscribers (telephones).

-- Each subscriber will originate one call during each two hours on the average.

-- Call durations will be exponentially distributed with mean durations, usually termed mean holding times of 3 min, 6 min, or 10 min.

- -- When an attempted call is not completed the call is lost. That is, the system provides a busy tone when an attempted call cannot be completed, and there is no provision for waiting or delayed calls. Such a system is termed a loss system.
- -- The probability of an attempted call not being completed, which is termed loss or blocking probability, is the proportion of attempted calls that are rejected. Our analyses use numerical values of 1%, 2%, and 5%.
- -- Attempted calls experience no blocking from limitations or architecture of the switching network. This condition is termed full availability.

The first step in a traffic analysis is to determine the traffic intensity for the offered traffic load using the expression

$$A = nc_{avg} \times t_m$$

where: A is the number of Erlangs,

nc_{avg} is the average number of attempted, or offered calls, and

t_m is the mean holding time.

Two examples are computed, first for 10 subscribers and mean holding time of 3 min, then for 20 subscribers and mean holding time of 10 min.

$$A_{10,3} = 10 \text{ subscribers} \times \frac{1 \text{ call}}{2 \text{ hrs}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times 3 \text{ min/call}$$

$$A_{10,3} = 0.25 \text{ Erl.}$$

$$A_{20,10} = 20 \text{ subscribers} \times \frac{1 \text{ call}}{2 \text{ hrs}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times 10 \text{ min/call}$$

$$A_{20,10} = 1.67 \text{ Erl.}$$

Other traffic intensities for the network and offered traffic loads assumed for these analyses are shown in Table E-1.

Table E-1. Traffic Intensities (in Erlangs) per Earth Station as a Function of Mean Holding Time and Number of Subscribers per Earth Station for an Average of One Call per Two Hours per Subscriber

Number of Subscribers per Earth Station	Mean Holding Time (min)		
	3	6	10
10	0.25 Erl	0.50 Erl	0.83 Erl
20	0.50 Erl	1.00 Erl	1.67 Erl

The next step in our traffic analysis is to use the offered traffic loads (traffic intensities) and acceptable blocking probabilities to determine the required number of circuits. This information is conveniently available in many published telephone traffic theory tables and charts. Traffic theory tables show offered load (A) in Erlangs as a function of various blocking probabilities (B), number of traffic sources (subscribers), and number of servers (circuits). The book by Siemens (1974) is one good source for such tables.

Using tables for loss systems with a finite number of traffic sources and full availability, we find that with ten subscribers the lowest number of circuits (servers) that will support 0.25 Erl of traffic with a blocking probability of 1% is three. (Three circuits actually will support 0.55 Erl of traffic from the subscribers, but two circuits will support only 0.18 Erl of traffic from ten subscribers, with blocking probability of 1%.) As another example, we show in Table E-1 that 20 subscribers for which the mean holding time is 10 min will provide an aggregated traffic load of 1.67 Erl. From the tables we determine that 20 subscribers offering 1.67 Erl of traffic require five circuits if the required blocking probability is 2%. (Five circuits will support 1.84 Erl, but four circuits will support only 1.20 Erl.) Table E-2 shows a tabulation of this type information for all combinations of offered traffic load (from Table E-1), numbers of subscribers providing the offered traffic, and selected blocking probabilities of 1%, 2%, and 5%.

Table E-2 Required Numbers of Circuits (Servers) to Support the Traffic Intensities Shown in Table E-1 for Blocking Probabilities of 1%, 2%, and 5%

Traffic Intensity, Erl/Earth Station		Blocking Probability		
		1%	2%	5%
0.25	(10,3)	3	2	2
0.50	(10,6) (20,3)	3	3	3
0.83	(10,10)	4	4	3
1.00	(20,6)	4	4	3
1.67	(20,10)	6	5	4

From Table E-2 we see that three circuits per earth station will provide a wide range of service capacity (Erlangs of traffic capacity) versus numbers of subscribers and blocking probability. We, therefore, use three circuits per earth station to determine the number of earth stations that can be supported in the network by 1/4 transponder of satellite resource.

The link budgets in Appendix D show the satellite EIRP that is required to support one carrier. Two carriers are required to provide a (duplex) circuit in a MESH network or between a remote station and the central station in a STAR network. Four carriers are required to provide duplex telephone service between two remote stations in a STAR network. These data have been used to develop Tables E-3 and E-4 which show the numbers of circuits that can be supported by 1/4 transponder. For the various values of earth-station figure of merit and required carrier-to-noise-power-density ratio, Table E-3 shows numbers of circuits possible in a MESH network and Table E-4 shows numbers of circuits possible in a STAR network between a remote station and the central station. Only half as many duplex service connections could be provided between two remote stations in a STAR network since four carriers are required for that type of two-hop service connection.

Following the assumption of three circuits per earth station and using the data from Tables E-3 and E-4, the maximum possible number of earth stations in a network is shown as a function of earth station figure of merit by curves which are parametric in required carrier-to-noise-power-density ratio. These curves are shown for MESH and STAR networks, respectively, in Figures E-1 and E-2 for an INTELSAT global-beam-coverage satellite resource, in Figures E-3 and E-4 for an INTELSAT hemispheric-beam-coverage satellite resource, and in Figures E-5 and E-6 for a Palapa A satellite resource.

To illustrate the utility of these curves, assume an RSP application for which the required carrier-to-noise power density is 54.0 dB-Hz and figure of merit for the (remote) earth stations has been selected to be G/T=25.0 dB/K. We note from Figures E-1 and E-2 that there could be four stations in a MESH network or seven remote stations in a STAR network supported by an INTELSAT global beam coverage satellite. From Figures E-3 and E-4, the comparative numbers are seven stations in a MESH network and 12 remote stations in a STAR network supported by an INTELSAT hemispheric beam coverage satellite. And from Figures E-5 and E-6 the respective numbers are 46 and 73 for a Palapa A satellite.

Types of service which will allow use of lower carrier-to-noise-power-density ratios will increase the number of circuits that can be provided by the 1/4 transponder, hence the number of earth stations in a network, each providing three circuits, will be increased. If digital technology is used, as we have discussed in Appendix A and various sections of the report, whereby two or more channels per carrier are provided, this would also increase the number of earth stations in the network.

Table E-3. Total Numbers of Telephone Circuits in a MESH Network That Can Be Supported By 1/4 Transponder For C/N_o = 48.0, 51.0, 54.0, and 57.0 dB-Hz and Receiving Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K

Transponder Resource	C/N_o (dB-Hz)			
	48.0	51.0	54.0	57.0
G/T = 17.5 dB/K				
INTELSAT, Global Beam*	9	4	2	1
INTELSAT, Hemi Beam**	16	8	4	2
Palapa A	104	52	26	13
G/T = 20.0 dB/K				
INTELSAT, Global Beam*	16	8	4	2
INTELSAT, Hemi Beam**	29	14	7	3
Palapa A	184	92	46	23
G/T = 22.5 dB/K				
INTELSAT, Global Beam*	29	14	7	3
INTELSAT, Hemi Beam**	52	26	13	6
Palapa A	322	161	80	40
G/T = 25.0 dB/K				
INTELSAT, Global Beam*	51	25	13	6
INTELSAT, Hemi Beam**	92	46	23	11
Palapa A	555	278	139	69
G/T = 27.5 dB/K				
INTELSAT, Global Beam*	90	45	22	11
INTELSAT, Hemi Beam**	162	81	40	20
Palapa A	941	472	236	118
G/T = 30.0 dB/K				
INTELSAT, Global Beam*	156	78	39	19
INTELSAT, Hemi Beam**	282	141	70	35
Palapa A	1545	774	388	194

*Available on INTELSAT IV, IV-A, and V Satellites

**Available on INTELSAT IV-A and V Satellites

Table E-4. Total Numbers of Telephone Circuits in a STAR Network (Central Station is Assumed to be an INTELSAT Standard B or Equivalent) That Can Be Supported by 1/4 Transponder For C/N_0=48.0, 51.0, 54.0, and 57.0 dB-Hz and Remote Earth Station G/T=17.5, 20.0, 22.5, 25.0, 27.5, and 30.0 dB/K

Transponder Resource	C/N_0 (dB-Hz)			
	48.0	51.0	54.0	57.0
G/T = 17.5 dB/K				
INTELSAT, Global Beam*	18	9	4	2
INTELSAT, Hemi Beam**	32	16	8	4
Palapa A	199	99	50	25
G/T = 20.0 dB/K				
INTELSAT, Global Beam*	30	15	7	3
INTELSAT, Hemi Beam**	55	27	13	6
Palapa A	338	169	85	42
G/T = 22.5 dB/K				
INTELSAT, Global Beam*	52	26	13	6
INTELSAT, Hemi Beam**	93	46	23	11
Palapa A	558	279	140	70
G/T = 25.0 dB/K				
INTELSAT, Global Beam*	84	42	21	10
INTELSAT, Hemi Beam**	151	75	37	19
Palapa A	879	440	220	110
G/T = 27.5 dB/K				
INTELSAT, Global Beam*	129	64	32	16
INTELSAT, Hemi Beam**	232	116	58	29
Palapa A	1301	652	326	163
G/T = 30.0 dB/K				
INTELSAT, Global Beam*	184	92	46	23
INTELSAT, Hemi Beam**	333	167	83	42
Palapa A	1781	892	447	224

*Available on INTELSAT IV, IV-A, and V Satellites

**Available on INTELSAT IV-A and V Satellites

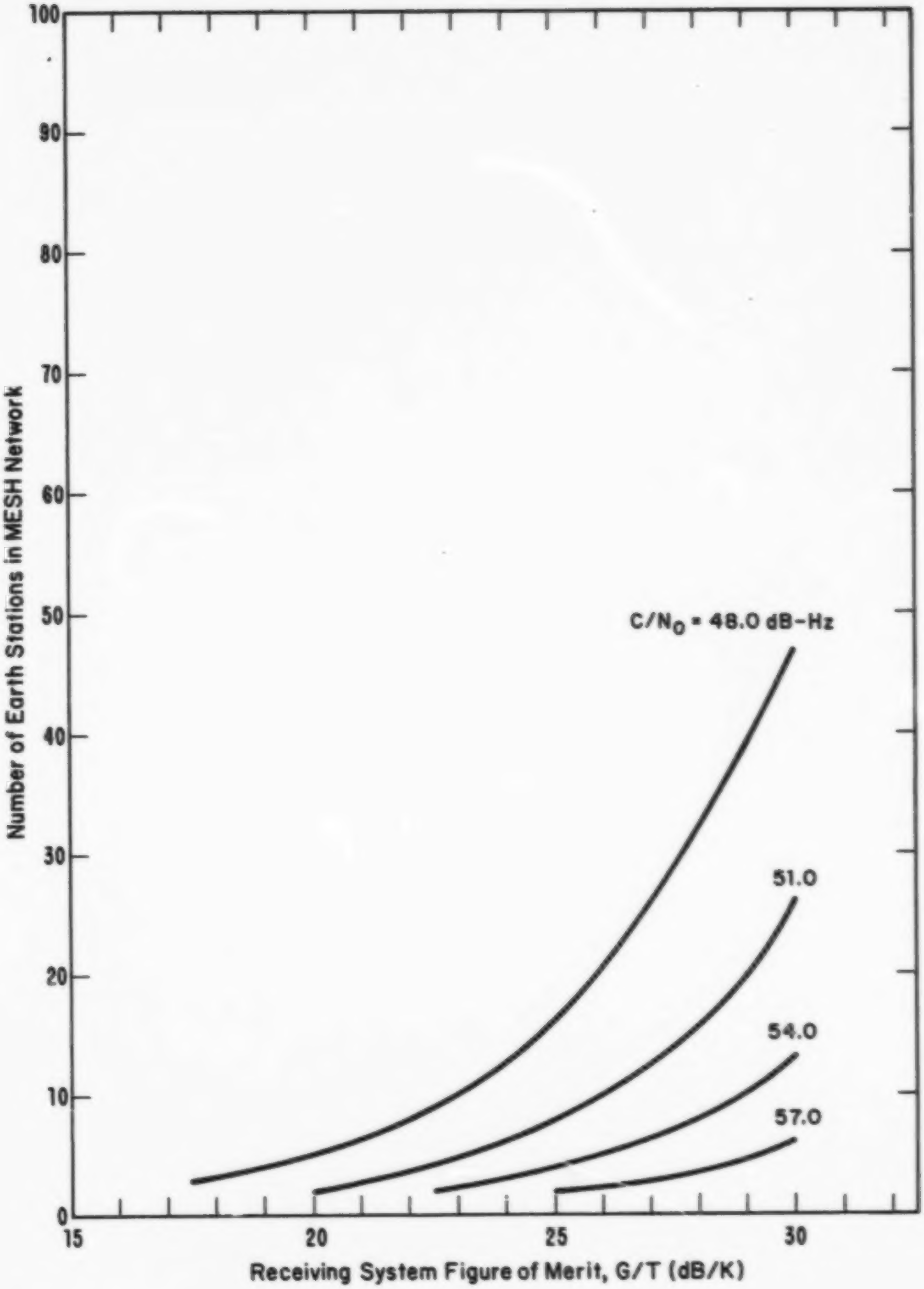

Figure E-1. Curves parametric in required C/N_0 showing the number of earth stations as a function of G/T that can be supported in a MESH network by 1/4 transponder on an INTELSAT global beam coverage satellite when three circuits are provided at each earth station.

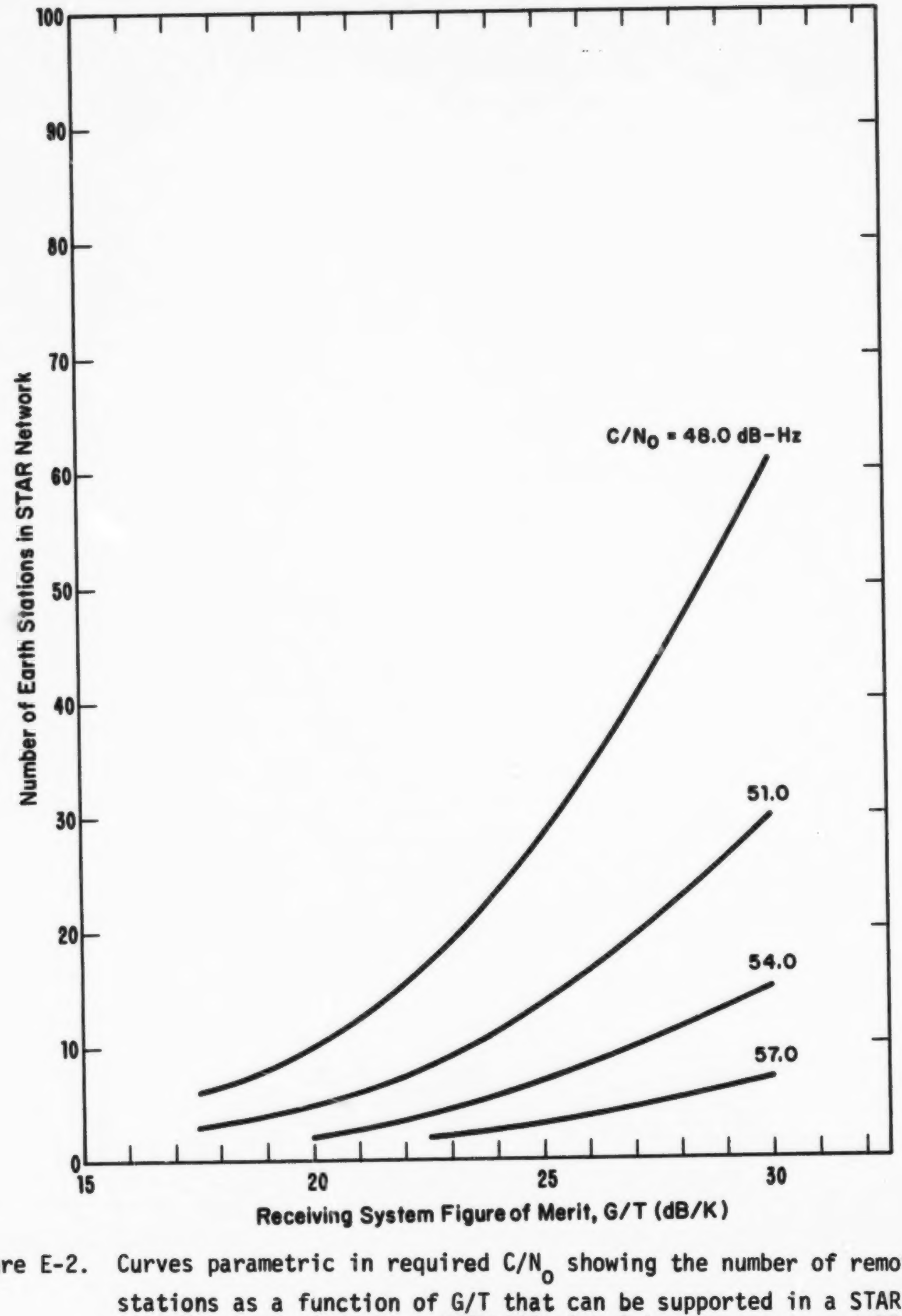

Figure E-2. Curves parametric in required C/N_0 showing the number of remote earth stations as a function of G/T that can be supported in a STAR network by 1/4 transponder on an INTELSAT global beam coverage satellite when three circuits are provided at each earth station. The central station of the STAR network is assumed to be an INTELSAT Standard B or equivalent capacity earth station.

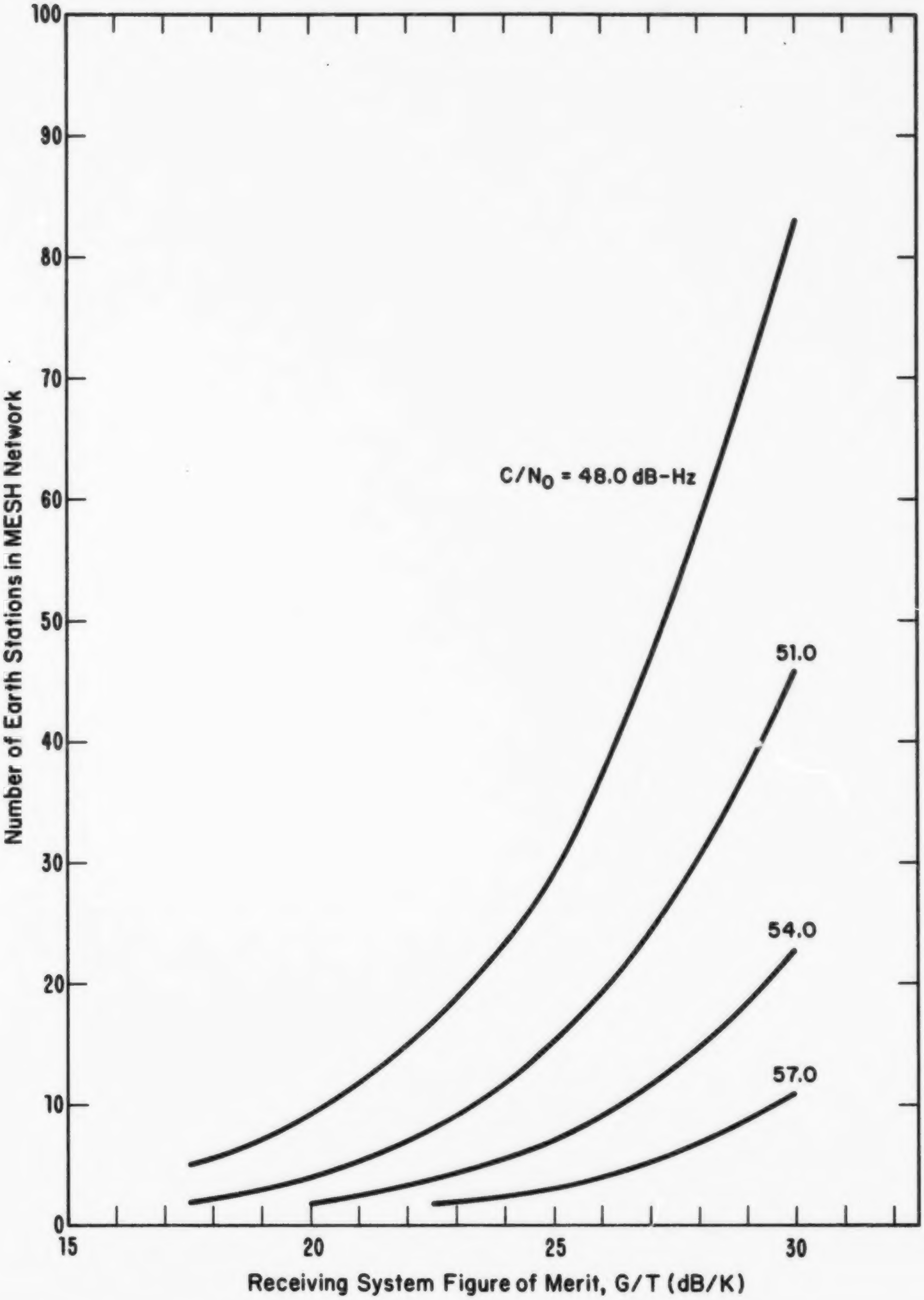

Figure E-3. Curves parametric in required C/N_0 showing the number of earth stations as a function of G/T that can be supported in a MESH network by 1/4 transponder on an INTELSAT hemispheric beam coverage satellite when three circuits are provided at each earth station.

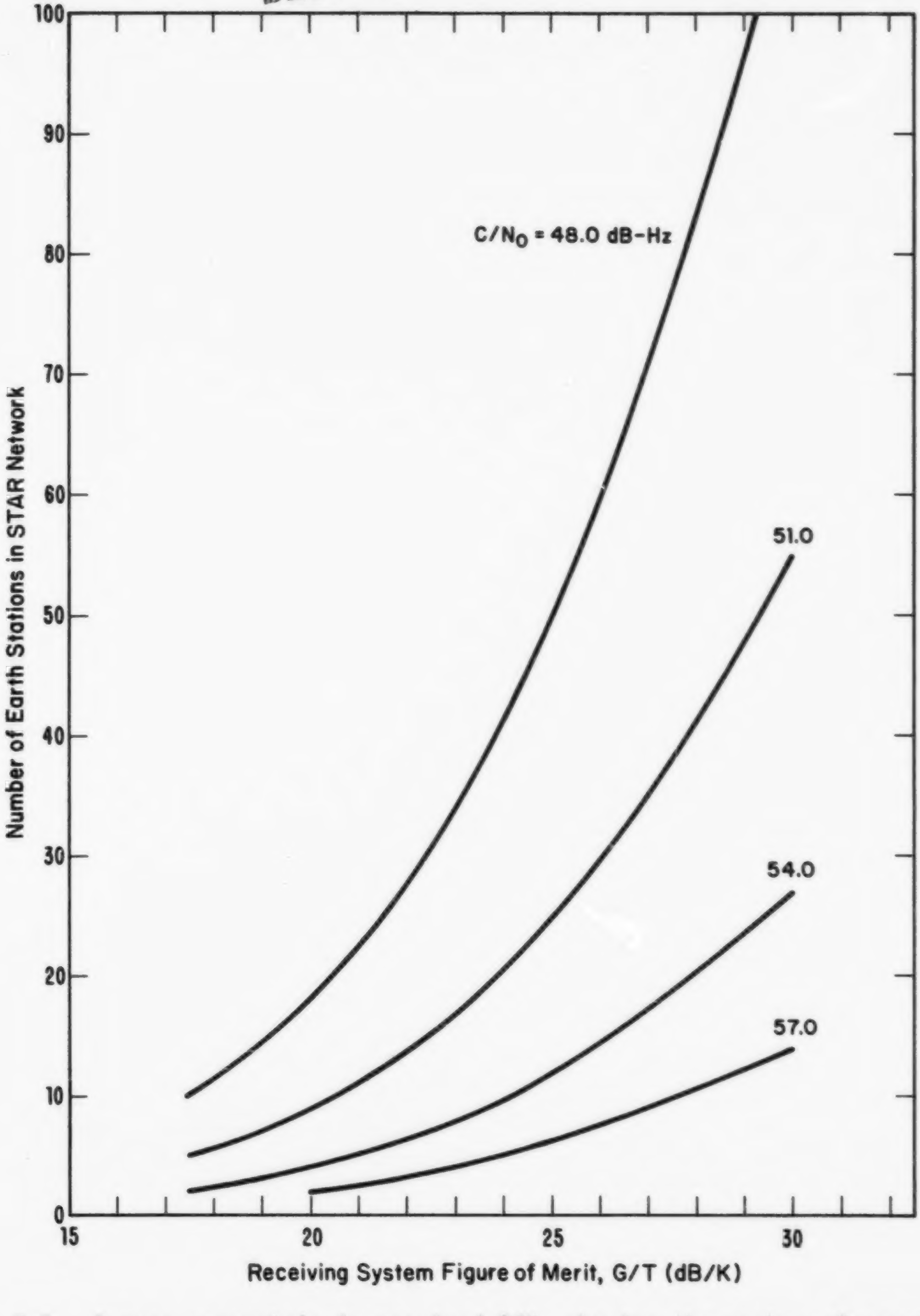

Figure E-4. Curves parametric in required C/N_0 showing the number of remote earth stations as a function of G/T that can be supported in a STAR network by 1/4 transponder on an INTELSAT hemispheric beam coverage satellite when three circuits are provided at each earth station. The central station of the STAR network is assumed to be an INTELSAT Standard B or equivalent capacity earth station.

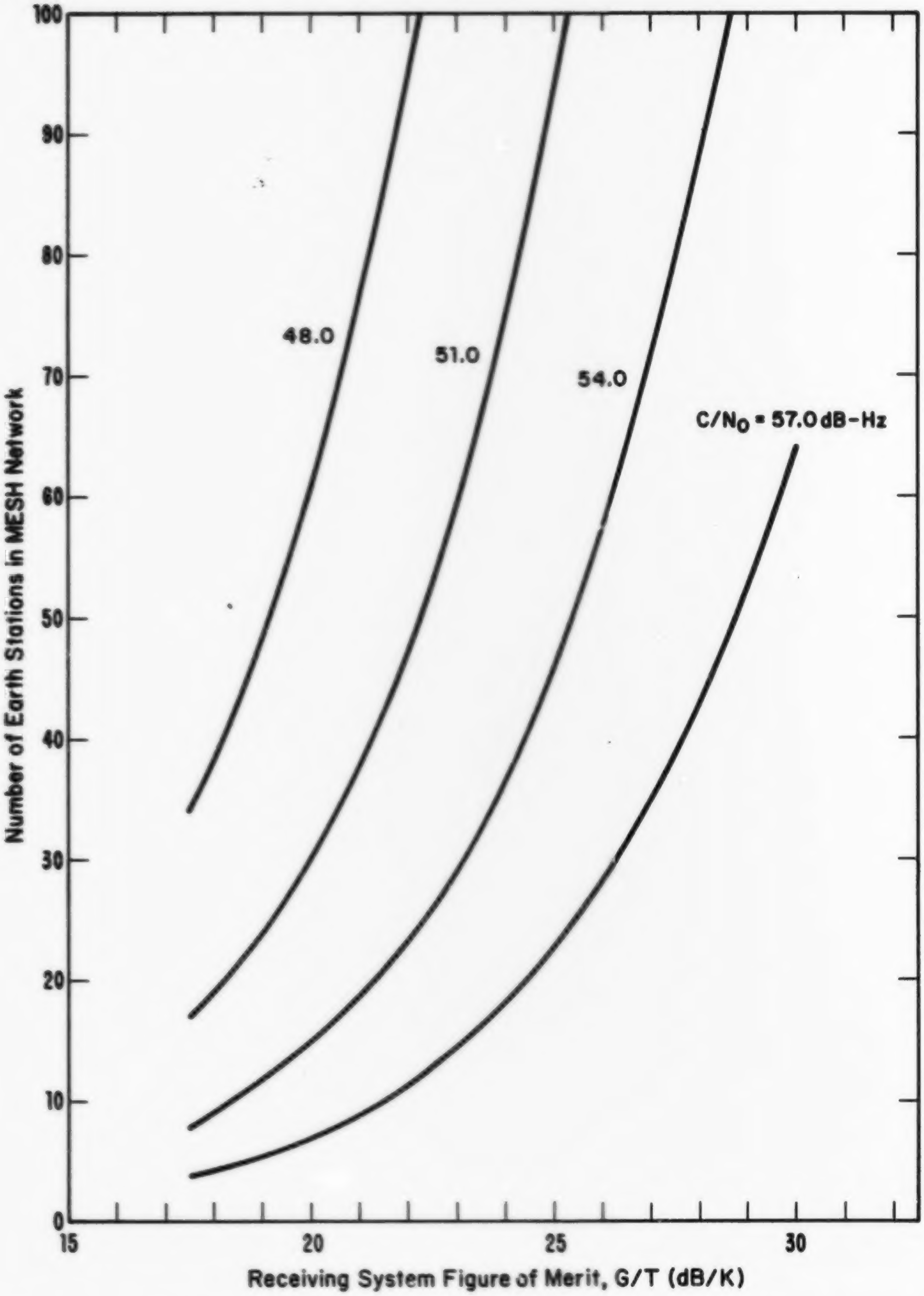

Figure E-5. Curves parametric in required C/N_0 showing the number of earth stations as a function of G/T that can be supported in a MESH network by 1/4 transponder on a Palapa A satellite when three circuits are provided at each earth station.

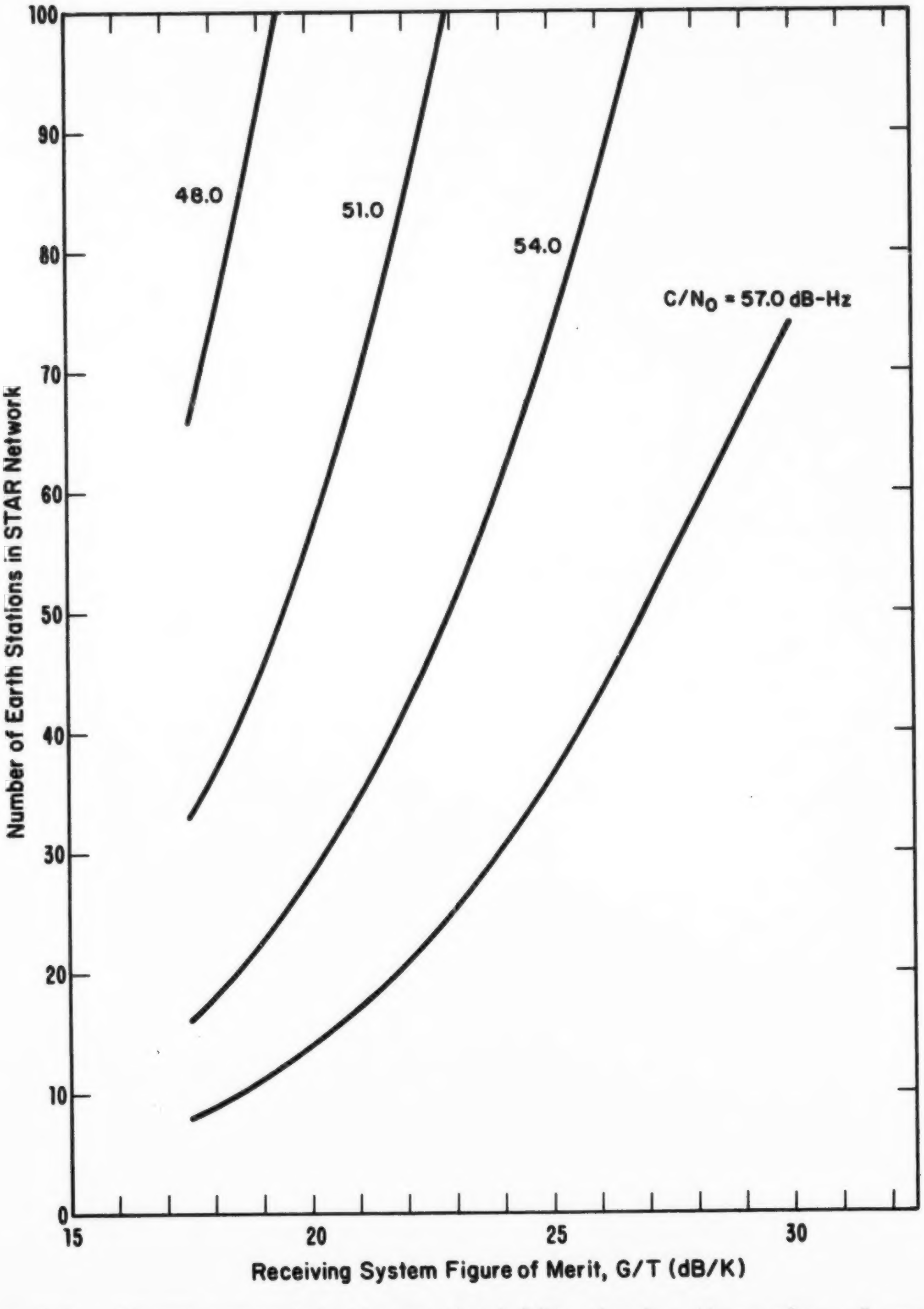

Figure E-6. Curves parametric in required C/N_0 showing the number of remote earth stations as a function of G/T that can be provided in a STAR network by 1/4 transponder on a Palapa A satellite when three circuits are provided at each earth station. The central station of the STAR network is assumed to be an INTELSAT Standard B equivalent capacity earth station.

REFERENCE

Siemens (1974), Telephone Traffic Theory Tables and Charts, Part 1, 2nd Revised Edition (Siemens AG, Munchen, Germany).

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Satellite communications are likely to be used to provide thin-route telephone service in developing countries only if the cost of earth stations can be substantially reduced. A parametric analysis of earth-station design and service capabilities is presented. Parameters of the analysis include six values of earth-station figure of merit, G/T, ranging from 17.5 to 30.0 dB/K, five values of antenna diameter ranging from 3.0 to 10.0 m, low-noise amplifier temperatures ranging from 55 to 200K, high-power amplifier output powers ranging from 1 to 400 W, INTELSAT and Palapa (typical of many domestic satellites) satellite resources, and frequency modulation as well as digital encoding with phase shift keying for voice service. Link budgets are developed from which the numbers of carriers that can be supported by 1/4 transponder are calculated. Assuming single channel per carrier as well as multiple channels per carrier service, the numbers of duplex telephone circuits per 1/4 transponder are calculated. Traffic analyses are performed to demonstrate the relationships between numbers of telephone subscribers per earth station, numbers of circuits provided at each earth station, and quality of service. Sampled cost information is presented and used to estimate earth station costs.

Key words: earth-station cost; earth-station design; satellite communications; telephones; thin-route applications; traffic analysis

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